Technical Note N-1303

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ABSTRACT

A state-of-the-art study was made of submarine electro-mechanical cable technology. These are ocean cables which include electrical cables with special strain members. The purpose of the study was to define areas of deficiencies so that development programs could be initiated in selected areas.

The approach included a literature search, and extensive interviews with electro-mechanical cable manufacturers and electro-mechanical cable users. Engineers and scientists of various disciplines from the Naval Civil Engineering Laboratory participated in the study. Areas of study include:

- Mechanical Properties
- Electrical Properties
- Handling
- Terminations and Hardware
- Maintenance and Repair
- Manufacturing
- History of Electro-Mechanical Cable Development

The technological development of submarine electro-mechanical cables dates from the mid-nineteenth century with their use as telegraph and, later, telephone cables. There is, therefore, a voluminous literature on ocean bottom communication cables. The wide use of electro-mechanical cables suspended above the seafloor began within the past twelve years. These cables include electro-mechanical cables deployed above the seafloor and can, with few exceptions, be included in two categories: structural cables, used as tensile members in support of structures tethered to the seafloor; and working cables, typically deployed and retrieved by winch into the sea from a surface or subsurface platform. A special case of working electro-mechanical cables, oil well logging cables, have technological developments dating back to the 1930's.

Electro-mechanical cable technology has benefited from communications and well logging technology, but deficiencies are still present. These deficiencies can be generally categorized in the four areas of: design of electro-mechanical cables and terminations; specifications and testing; handling; and repair and maintenance.

Design problems include such things as conductor materials, strength member materials, terminations and intended usage. The study indicated that specification writing is an area which could be improved, especially with regard to testing. This stems partially from the lack of knowledge on the specifiers' part and partially from the lack of adequate test procedures and facilities.

Handling of cables is one of the most deficient areas and carries a high urgency to improve techniques and hardware for proper handling and deployment. The failures experienced have yet to be fully understood.

Cost saving is ample justification for improving repair methods and developing proper maintenance procedures.

Areas of suggested electro-mechanical cable development are:

1. Testing standardization
2. Specification standardization
3. Failure mechanisms analyses
4. Standardize handling methods
5. Corrosion
6. Torque balancing
7. Develop a better field splicing technology
8. Use of synthetics as strength members
9. High power transmission
10. Terminations such as connectors

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I. INTRODUCTION

The use of E-M (electro-mechanical) cables in fixed ocean installations has become an area of concern to the Navy which has recently begun to construct such installations on the deep seafloor. One major factor in determining success or failure of militarily significant installations is the proper use of cable, and its performing as specified. In order to improve the technology in E-M cables for such installations, a thorough look at past experiences, present technology, and into the future is necessary.

There are three types of cable in use in the ocean today, electrical cables, mechanical cables, and E-M cables. For purposes of this study, only E-M cables are considered. An E-M cable is defined as a cable used in support of, a component of or part of a fixed ocean installation; containing electrical conductors, either power or signal, or both; and a strength member, under continuous or intermittent loading. The electrical function of the cable is transmission and distribution of power, or signal communication, or both. The strength member is for tensile loading. A fixed installation includes such systems as cable arrays, and manned or unmanned structures.

An electrical cable with armor that serves only for protection, rather than load bearing is not the type of cable to which this study is addressed. Tow cables or cables used in ship or vehicular systems are not included except where a problem associated with these cables is applicable to the E-M cables considered. Seafloor, or E-M ocean cables are laid on the ocean floor and see only their own weight during handling and deployment, but usually are under some additional tension when installed. These cables may have a strength member, but the oceanic E-M cables are considered in this study to a lesser degree than the other electro-mechanical cables.

Two types of suspended electro-mechanical cables are the objects of this study. They are working E-M cable and structural E-M cable. The working cable is one which supports a load in excess of its own weight during repeated raising and lowering operations. It may be fixed at both ends or may have one end fixed and the other free to rotate. The load may be continuous or may be relaxed, e.g., when the load is set on the ocean floor. A system used for support of a fixed installation would be the Seafloor Deep Corer, which is approximately 8 tons in water, is raised and lowered on a 1 1/2-inch-diameter cable which supplies power and signals to the system when it is on the seafloor. A structural cable is that part of the installations which is not generally raised and lowered repeatedly, but remains in the ocean providing an electrical and mechanical function. An example of such a cable is that used in surveillance arrays between acoustic sensors. To maintain a given configuration, the cable must be under tension.

Although seafloor and suspended E-M cables have been used in the ocean for years with a high degree of success in some applications, many new uses are being conceived. It is these new requirements which are pushing the technology into areas requiring the ultimate in reliability under the most severe conditions. Considerable time and money are being spent on design and handling each time an electro-mechanical cable is used for a

new application in the ocean. An engineering analysis of electro-mechanical cable is presently difficult due to the lack of data from actual ocean usage.

Literature surveys, conducted as part of this study, reveal only a minimum of data in very specialized areas. Seafloor cables have benefited from years of private industry money being invested for research in developing the technology of design and handling of these cables. E-M structural cables deal with a relatively new application and, information is not available in the literature for two reasons, first the classified nature of the application and, secondly, many implants have been unsuccessful.

Recent problems with the cables of Project SEA SPIDER, AFAR, LRAPP, and some of the E-M working cable problems such as on DOTIPOS, have focused attention on long lengths of cable. In each of the above-mentioned projects the E-M cable was sufficiently damaged either through improper handling or improper design, to make the system inoperable. The high cost of placing material and equipment in the ocean warrants a thorough evaluation of the problems associated with long lengths of E-M cable.

A personal contact survey was conducted by engineers from the Naval Civil Engineering Laboratory who visited most of the American manufacturers and many of the users of electro-mechanical cables of the types discussed above. Questionnaires were filled out for each of the types of users and for each of the cables they used. Representative questions dealt with cable description, application, problems, and recommendations as to where future research efforts could best aid in eliminating the deficiencies in the technology.

II. MECHANICAL PROPERTIES, MATERIALS, AND CONFIGURATIONS OF LOAD-CARRYING COMPONENTS

Background

E-M cables can be purchased off the shelf from a number of manufacturers.[1,2] The construction of such cables usually consists of (1) centrally located conductors (coaxial or multiple pairs); (2) a layer of insulation; and (3) two contrahelically-wound layers of steel armor. Often these off-the-shelf cables do not meet requirements of the user and, as a result, most cables are purchased on special order; specified, designed, and fabricated for a particular purpose. An example of such a cable is shown in Figure II-1.

In reviewing cable failures, it was found that many problems arose out of five causes:

1. User did not know what cable was needed to provide proper performance;
2. User applied cable to a purpose for which it was not originally intended;
3. Manufacturer bid for and attempted to make the cable beyond his technical abilities;
4. Manufacturer made the cable from incomplete specifications or without knowing the intended purpose; and
5. Manufacturer and user never tested sample of the cable to see if it met all of the design specifications.

There are areas of E-M cable technology that need improvement, particularly in the types of material used as the load-carrying member and the configuration of such members within the cable design. The resulting mechanical properties and behavior that are exhibited by the armoring and load-carrying members of the cable are also areas that need further research.

Materials

The materials that have been used as strength members in E-M cables are shown in Table II-1. Other materials[3] that can be used as load-carrying members and armor include low carbon steel, plow steel, extra plow steel, copper-covered steel, cadmium bronze, and beryllium copper. These other types of material are suggested for use in special environmental, magnetic, weight, strength, or other requirements.

The material[3] most commonly used as a strength member is galvanized improved plow steel. The tensile strength of this material varies with the wire diameter as shown in Figure II-2. Variations in the tensile strength for a given diameter occur because of differences in actual diameter and slight variations in the manufacturing process. The dashed line represents the average tensile strength and is used for design purposes. For comparison purposes, Figure II-3 shows the tensile strength properties of stainless steel wire types.

The primary advantage of steel is the large strength-to-diameter

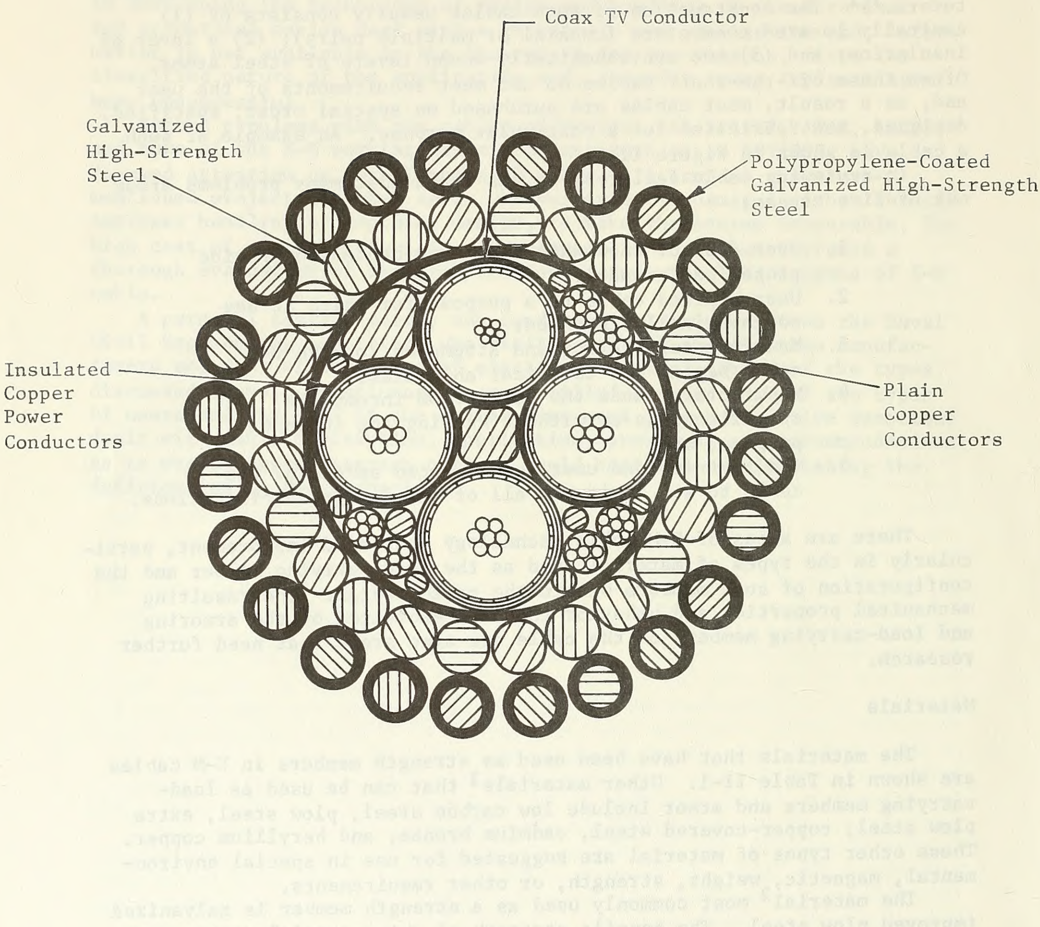

Figure II-1. Example of a contrahelically-wound steel armored electro-mechanical cable. (This cable has been manufactured for the NCEL Seafloor Deep Corer System.)

Table II-1. Material Types Used as Load-Carrying Components of Electro-Mechanical Cable

Material	Tensile Strength ($x10^3$ psi)	Modulus of Elasticity ($x10^6$ psi)	Break Elongation (%)	Specific Gravity	Approximate Cost Per Pound ($)	Manufacturer
Improved Plow Steel (Galvanized)	See Figure II-2	28.0	1½-3	7.85	0.25	U. S. Steel Corp.
Stainless Steel (Type 302 & 304) (Type 305 & 316)	See Figure II-3	29.0 29.0	50 50	8.02 8.02	1.64 1.91	U. S. Steel Corp.
Dacron (T-68)	163	2.0	15	1.38	0.81	DuPont de Nemours & Company
Fiberglas (Type ECG-75 5/3 063)	135	10.5 (at 72°F)	3.0-3.5	2.54	1.20	Owens Corning Fiberglas Corp.
Nylon (T-728)	143	0.7	19	1.14	0.85	DuPont
Parafil (Type A&C) (Type D)	133 133	1.1 0.5	6 ?	1.23 1.23	0.85	ICI America, Inc.
PRD-49 (Type III) (Type IV)	400 430	18.6 12.1	2 3.3	1.45 1.45	\$50 for lots >100 lbs. \$50 for lots <100 lbs.	DuPont

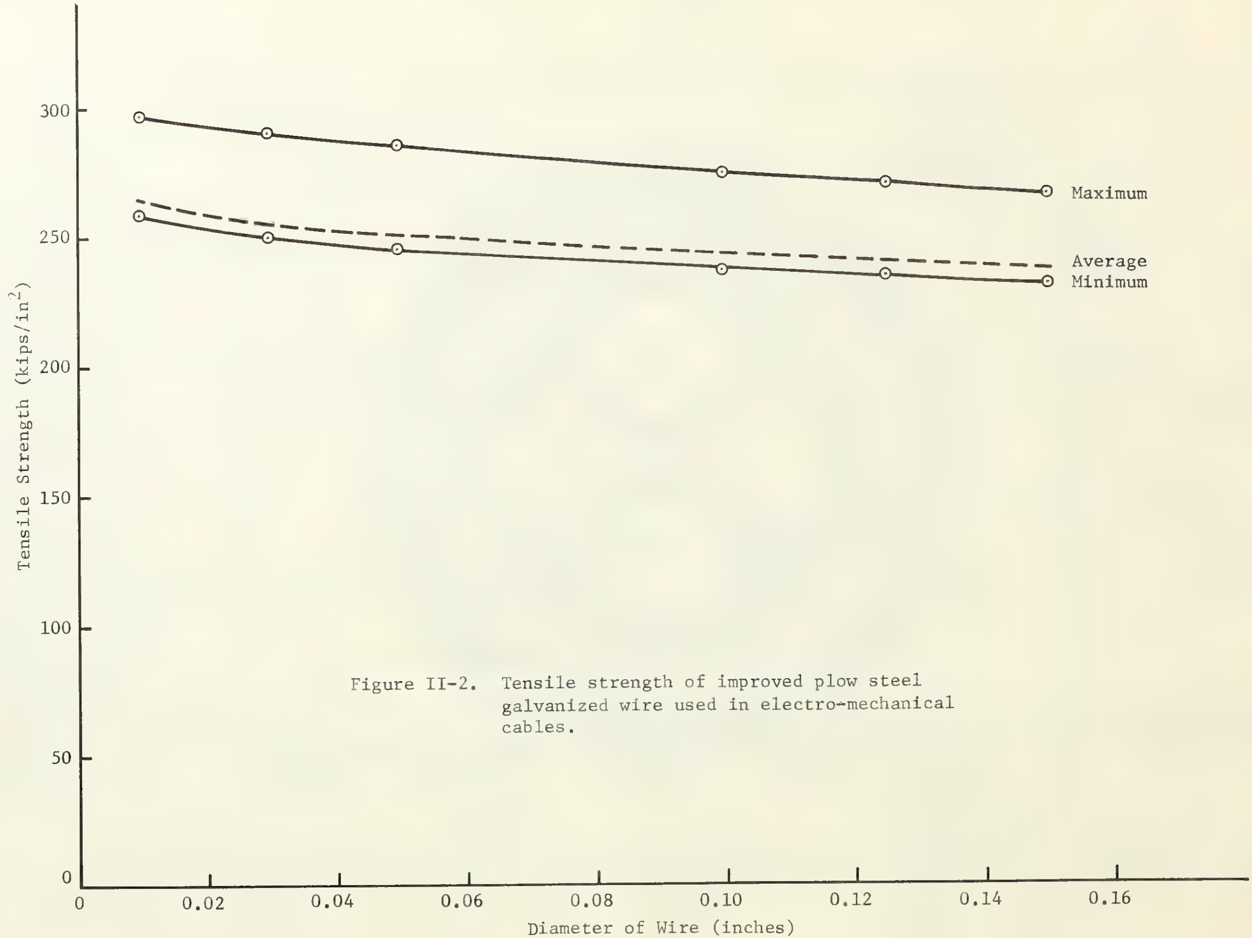

Figure II-2. Tensile strength of improved plow steel galvanized wire used in electro-mechanical cables.

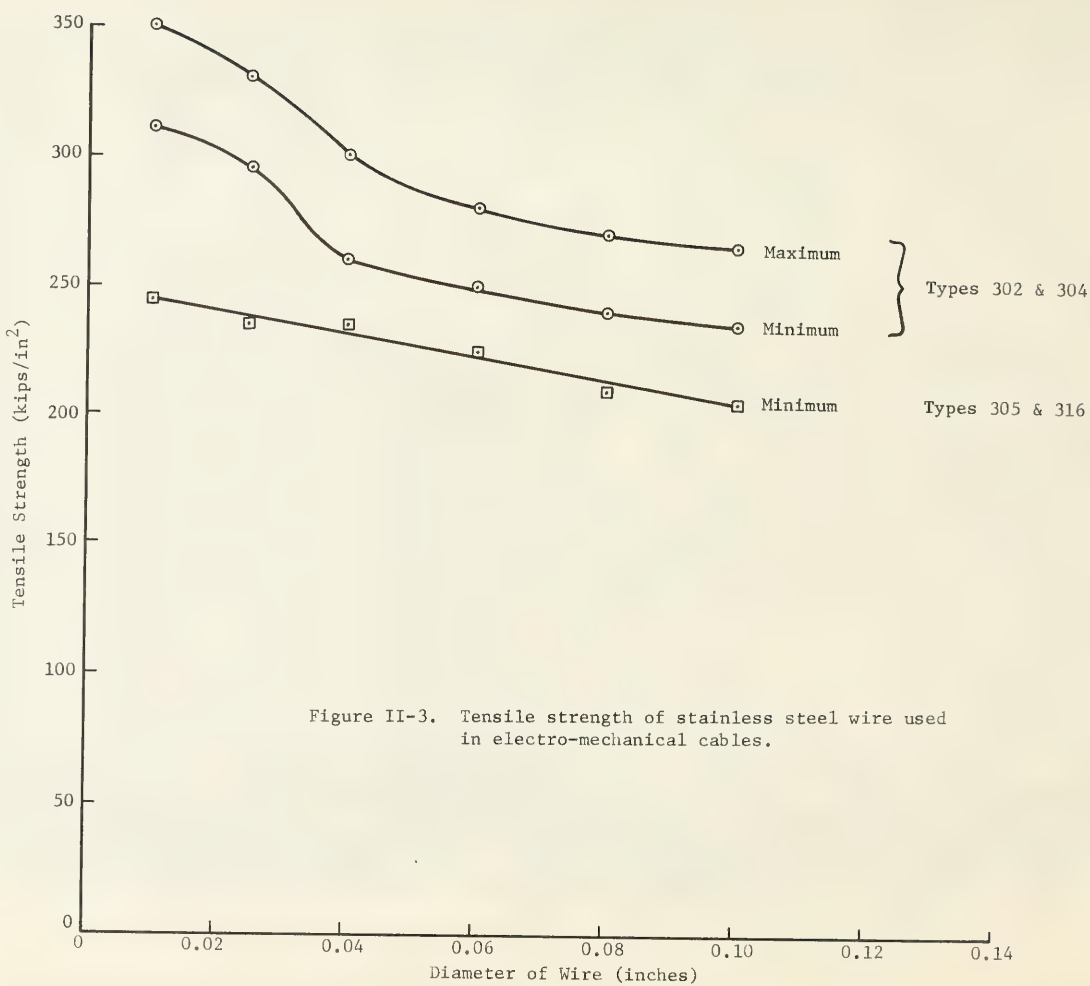

Figure II-3. Tensile strength of stainless steel wire used in electro-mechanical cables.

ratio which lowers the hydrodynamic drag. Steel is immune to fish bite but very susceptible to abrasions and corrosion. Its high in-water weight makes steel armoring depth limited.

Cable with metallic armor is quite stiff and requires a large bending radius. Titanium has been considered as a possible armoring material because of its high strength, but it generally is cost prohibitive for most applications (see Corrosion).

In general, synthetic materials have a number of advantages over their metal counterparts. These advantages are: (1) high strength-to-weight ratio; (2) relatively good flexibility; and (3) resistance to corrosion. Use of synthetics in the ocean environment, however, has been limited compared to the use of improved plow steel for cable manufacturing.

From Table II-1 and Figure II-2, it can be seen that the synthetic material "PRD-49" has a tensile strength about 1.6 times greater than improved plow steel and a specific gravity which is only 18.7 percent of improved plow steel. However, "PRD-49" has a modulus of elasticity about one half that of improved plow steel. This characteristic may be undesirable in applications where minimum elongations are a requirement. In working cable applications where bottom breakout force is involved, however, the lower modulus may be an asset. An important negative factor of "PRD-49" is its present very high cost when compared to improved plow steel or the other materials.

The synthetic, "Parafil",[5] shows promise in cable applications. "Parafil" is high-strength polyester filaments densely packed in a tough polyethylene sheath. The completely parallel construction makes the cable inherently torque-free and, thus, the cable will not rotate under load nor will it kink. It also exhibits several advantageous properties: (1) minimal creep (≈16 percent tension reduction after 100 weeks of loading to 80 percent of breaking strength); and (2) thermal stability.

Figure II-4 shows a comparison of the modulus of elasticity of the various materials used as strength members with the modulus of elasticity of copper[6] as manufactured for cables. It can be concluded from this figure that for the same unit elongation, stainless steel, improved plow steel, and "PRD-49" Type III will carry a larger tensile stress than copper when all these materials are compared in the form of a straight wire or yarn. On the other hand, "PRD-49" Type IV, Fiberglas Type ECG-75, Dacron, Parafil (Type A, C and D) and Nylon will carry less tensile stress than copper for the same unit elongation. Thus, this figure illustrates why a straight solid conductor should not be used for large load-carrying E-M cables, particularly if the synthetic materials with moduli of elasticity less than for copper are used. However, since copper usually is used in the form of braids and twisted multiple conductors, the design of an electro-mechanical cable can be such that all of the tensile load is carried by the strength members.

Types of Construction

The double layer, contrahelically-wound, external armoring described as the standard E-M cable is the basic type of construction for the strength member. The two contrahelically-wound layers can be manufactured

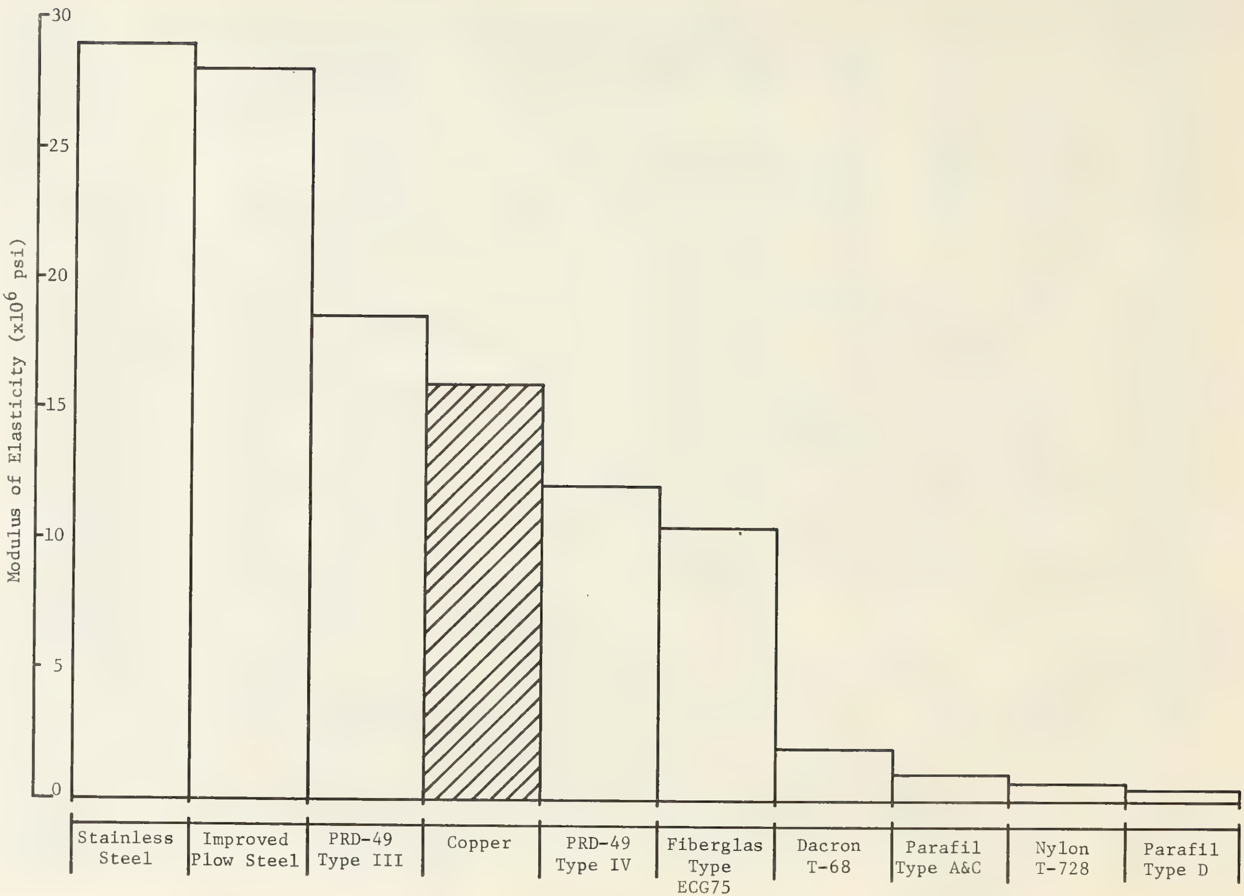

Figure II-4. Modulus of elasticity of various materials used in electro-mechanical cables.

to provide some torque-balancing that manufacturers advertise as "torque-free" or "no twist" cable. This technique to reduce cable twisting attempts to equalize the opposing strain energies stored in the contra-helical lays. However, the strain energies can be equalied only if the amount of torque in each layer is equal.

The external armoring prevents crushing of the cable wound on a spool. Protection against abrasion to the armor wires is sometimes provided by coating the individual wires and fibers with polyethylene or urethane. Still another variation of the contrahelical external armoring is the jacketing of the entire cable with a layer of poly-ethylene or urethane. Table II-2 lists a number of jacketing materials and their physical properties. This coating intrudes between the armor layers and provides not only abrasion protection, but aids torque-balancing and extends the fatigue life[8] of the cable.

A radical departure from external armoring is a central core strength member cable. The breaking strength of this type of cable is simply that of the central core, and electrical breakouts are easily accomplished.

Synthetics used as strength members are usually braided or con-structed as parallel fibers. Advantages of braided synthetics include reduced elongation and increased abrasion resistance to the core, while one disadvantage is the reduction of cable breaking strength.

By making the synthetic fibers truly parallel the tensile strength can be increased two to three times. Since each filament is carried entirely and equally in tension, there are no isolated stress concentra-tions that can result from overlapping layers in braided fibers. This means that the cable has a longer expected working life. However, paral-lel filament construction makes it more difficult to provide a satis-factory mechanical termination than contrahelically-wound external armor.

Combinations of armor materials have been used in the construction of E-M cables. An example of such a cable was manufactured by South Bay Cable[9] for Bell Laboratories that contained fiberglass and improved plow steel.

In the construction of double-armored steel E-M cables the cable breaking strength varies directly with the cable diameter. Figure II-5 gives approximate amounts for the breaking strength that can be expected for a given cable diameter. (Data for the figure, except where noted, were obtained from Reference 1.) Double-armored construction, however, is not the only construction that is used. Manufacturers[1,9] claim that they can produce E-M cables with more than two armor layers. Breaking strengths for a given diameter can, therefore, be increased but the space for conductors is proportionately decreased.

Failure Mechanisms

During the review of the mechanical and material properties, it appears that knowledge gained from wire rope technology is directly applicable to the strength members of E-M cable. Two explicit examples are: (1) the use of steel or steel alloys as the armoring material; and (2) the contrahelical winding of armor. This typical E-M cable construc-tion is subject to two major failure mechanisms, kinking and fatigue.

Table II-2. Properties of Extruded Jacket Materials[7]

Property	Hypalon Chloro-sulfonated Poly-ethylene	Nitrile Rubber Nitrile-Butadiene Vinyl	Nylon Polyamide	Neoprene Poly-chloroprene	Polyethylene Copolymer	Adiprene Polyurethane (Ether)	PVC Polyvinyl-Chloride	Kynar Polyvinyi-Idene Fluoride
Abrasion Resistance	Excellent	Excellent	Excellent	Excellent	Good	Excellent	Good	Good to Excellent
Brittleness Temperature, ° C	-43 to -57	-46	-65 to -80	-68	-76	-51 to -62	-20	-40
Compression Set Resistance	Fair	Good	Good	Fair	Fair	Excellent	Good	Good
Elongation, %	700	400-700	200-700	800-900	100-600	200-600	200-400	
Flexibility, Low Temperature, ° C	-23	-45	-65 to -80	-54	-51	-54	Special Compounds to -40	Fair
Fungus Resistance	Very Good	Good	Good	Excellent	Excellent	Good	Good	Good
Hardness	Shore "A" to 95	Shore "A" 40 to 90	Rockwell III	Shore "A" 20 to 95	Shore "D" 41 to 70	Shore "A" 20 to 100	Shore "A" 83-95	Shore "A" 50-60
Impact Strength	High	Medium	High	High	High	Very High	Fair to Good	
Resilience	Medium	Excellent		High		Very High	High	Medium
Specific Gravity	1.12-1.28	0.98-1.10	1.07	1.23-1.25	0.95	1.06	1.2-1.5	1.85
Tear Resistance	Fair	Excellent	Excellent	Good	Fair	Excellent	Fair	
Tensile Strength, psi	3000	2200-4500		3500	2000-2500	4000	3000	2000
Water Absorption Resistance	Very Good	Fair	Poor	Fair	Excellent	Very Good	Fair	Very Good
Chemical Resistance Resists What	Alkalies, Solvents, Oils, Dilute Acids	Aliphatic Hydrocarbons, oils	Weak Acids, Sunlight, Alkalies, Organic Acids	Oils, Gasoline, Aliphatic Hydrocarbons, Sunlight, Heat Aging	Alkalies, Oils, Solvents, Dilute Acids	Oils, Gasoline	Oils, Acid, Alkalies	Oils, Chemicals, Solvents and Exotic Fluids
Susceptible to	Moisture, Weather	Aromatic Hydrocarbons, Dissolves in Alcohols	Strong Acids	Chlorinated Hydrocarbons	Strong Acid, Oxidation, Soluble in Aromatic Solvents	Alkalies, Hydrocarbons, Flammability Poor	Acetates, Acetone, Aromatic Hydrocarbons, Esters-Ketones, Lacquer Thinners	

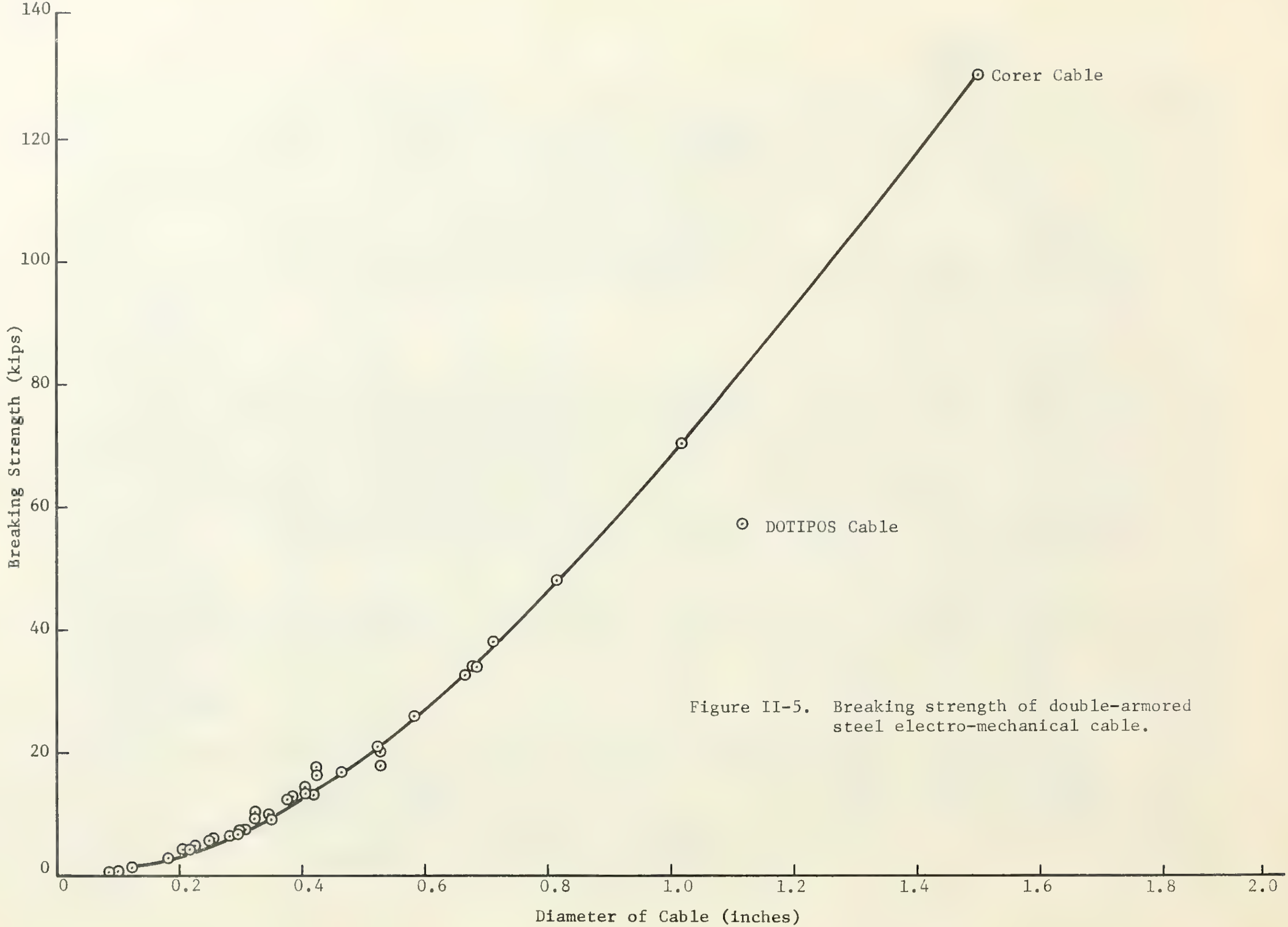

Figure II-5. Breaking strength of double-armored steel electro-mechanical cable.

One form of kinking occurs as a two-step mechanism. A cable can rotate and accumulate torque, which is released in the form of a loop when the cable becomes slack. This loop is pulled into a kink, causing permanent deformation when the cable becomes taut again. Even if the kink itself did not leave the cable inoperable by breaking the conductors, a kink severely reduces the cable life by exposing wires to corrosion and producing a weak point under cyclic loading.

Kinking can be formed by improper torque balancing. As discussed earlier, even though manufacturers claim that they can make "torque-free" or "non-rotating" electro-mechanical cable, there is no contra-helically-wound cable manufactured that can demonstrate this capability. Parallel filament synthetics do not have inherent residual torsional stresses and should be torque-free.

Fatigue usually is the result of cyclic loading, such as running over sheaves during deployment and recovery operations and action over a pulley or sheave due to ship motion. This repetitive bending, leading to fatigue failure, is difficult to detect because the internal conductors are being damaged. The copper wires are cold-worked due to the bending, and the result is usually an electrical, not a mechanical, failure. To prevent fatigue failure: (1) the cable should not be subjected to any reverse bending during sheave passage; (2) both the recommended sheave groove size and minimum bending radius for that particular electro-mechanical cable should be used to design the proper sheaves; and (3) a sample of the cable should be fatigue tested to determine its expected working life.

Improper sheave groove size and rubbing of overlaying armoring contribute to abrasion of the external wires of the cable. These wires become notched, and fatigue failure occurs under continued bending and tensile loading. Protection against abrasion can be provided by polyethylene or urethane jacketing over individual strands and/or over the entire cable.

Terminations are subject to fatigue due to bending and twisting of the cable just above the connection, which must by nature be rigid. This action can deteriorate the wires in the termination and birdcage the external armor above the connection. Birdcaging can permanently deform the armor and increase the possibility for corrosion. Fixed terminations must be relieved by swivels and ball or pinned joints to eliminate bending and torsional moments.

Since the use of synthetic materials as armoring is relatively recent, the failure experience of E-M cables using these materials is not known at this time.

Design and Testing of E-M Cable

In order to guard against these probable failure mechanisms, the user should realize the limitations of his particular E-M cable. This requires knowledge of the cable mechanical properties, including parameters such as strength, bending, and torsion.

To design for strength the user must decide what maximum working load he will encounter and the safety factor he desires for the specific application. Once the working load and safety factor are determined, the

breaking strength of the cable can be calculated. The manufacturer usually will test the particular E-M cable in pure static tension for adequate breaking strength and determine the modulus of elasticity of individual armoring wires. From Young's modulus the longitudinal spring constant can be determined for a cable with a specific area and length.

The other two important mechanical properties, bending and torsion, should be considered and determined for each particular E-M cable as well as the tensile breaking strength. The user must recognize potential flexural and torsional problem areas such as sheave passage, fixed terminations, cyclic loading due to currents and wave action, and ship motions and payload response. If the user has a working knowledge of his entire cable system, then he should be able to predict the allowable limits on the bending and torsion parameters. The resulting design specifications to the cable manufacturer should have details which reflect such knowledge of the system.

Once the cable is fabricated, a sample should be tested to verify that the manufacturer met all of the design specifications. The tests performed should determine:

Effect of sheave size (minimum bending radius)
Effect of sheave groove size
Effect of fleet angle and level wind
Bending fatigue over sheaves
Cyclic loading due to transverse vibrations
Natural frequency versus length curves in strumming mode
Load versus rotation curves

Since most manufacturers make only special order E-M cable, they do not have permanent facilities to perform these tests. The extent of their testing is the determination of the breaking strength and modulus of elasticity. Manufacturers, at a premium cost, can do the tests by setting up the facilities for any particular cable.

Corrosion of Electro-Mechanical Cables

Metal wires can have a high strength-to-diameter ratio which, coupled with their flexibility and ease of manufacture, make them ideal candidates for strength members in electro-mechanical cables. However, many metals and alloys are subject to corrosive attack when they are exposed to seawater. For cable lifetimes of up to six months, such attack is normally insignificant; however, for long-term exposure in terms of years, such attack may be the limiting factor in cable design.

The information included in this section is not based upon actual exposure of E-M cable to the ocean environment but is based upon an analysis of pertinent information gathered in marine corrosion tests on plate and sheet materials and wire rope.

The most common material presently used for strength members of E-M cable is carbon steel. Referred to as plow steel, improved plow steel, extra improved plow steel and several trade names, this material is inexpensive, easy to fabricate and has a high strength/weight ratio. All types of carbon steel are, however, subject to uniform corrosion when

exposed to seawater. Corrosion rates of bright steel are initially in the range of from .003 inch to .008 inch per year during the first year of exposure. This rate decreases with time to a range of from .001 inch to .005 inch per year after three years. Thus, the percentage of original breaking strength remaining after exposure is primarily dependent on the original wire diameter and time of exposure. The cross-sectional area and, thus, the breaking strength of a large wire is less affected than that of a small wire when equal losses of diameter are experienced. Abrasion of the wires during exposure can greatly increase the corrosion rate of carbon steel. In fact, exposure to constant abrasion like that of sand in the surf zone can cause corrosion rates as high as several inches per year.

The corrosion of carbon steel wires in electro-mechanical cables can be mitigated in several ways. The most obvious is to isolate the wires from the seawater by some type of protective jacket. However, in cables of practical length, complete protection is rarely, if ever, achieved because of permeable materials, cracks and access of water at terminations. Also, abrasion can expose the underlying wires and allow corrosion to occur. Carbon steel wire will corrode at such exposed areas at the same rate as unprotected cable if the exposed areas are large and at a reduced rate if the exposed areas are very small, say, due to pin hole imperfections in the jacketing. Coatings of anodic metals can also effectively mitigate the corrosion of carbon steel wires. They have an advantage over inert jacketing in that their protection can extend over small distances even when breached by defect or damage.

The most common type of anodic metal coating is hot dip galvanizing. In this process the wires are passed through a molten zinc bath which coats the wires with a complex zinc-iron alloy which is anodic to the underlying steel wire. Normal coating thicknesses of .0005 inch to .002 inch can prevent corrosion of the wires for periods of up to two years, depending on coating thickness. However, the process reduces the strength of the wires by approximately 20 percent. After the coating is corroded or abraded away, the underlying carbon steel wire will corrode at the same rate as uncoated wire.

Another common type of anodic coating is hot dip aluminizing. Similar to galvanizing, aluminizing protects the steel wire with a complex aluminum-iron coating which is anodic to the underlying wire. Aluminized coatings are normally thinner than galvanized coating (.0003 inch to .001 inch versus .0005 inch to .002 inch) but have similar lifetimes and properties. They, too, reduce the strength of the wire.

Hot dip coated carbon steel wires of usual diameter (.030 inch) can be expected to last from three to five years with less than a 50 percent loss in breaking strength. Jacketing of similar wires will increase their lifetime to four to six years.

Anodic coatings, either aluminum or zinc, applied by electroplating methods have the advantage of not affecting the strength of the material coated. However, due to their composition and porosity they are poor substitutes for the hot dip applied coatings.

All stainless steels are subject to crevice corrosion in seawater. Since the strength members in an E-M cable will normally be exposed in a

manner conducive to crevice attack, i.e., proximity of adjacent wires and inner sides form crevices, this places a severe limitation on the long-term use of stainless steel outer strength members in electro-mechanical cables. Those stainless steel wires in or under the jacket may be acceptable. Some stainless steel alloys are, however, superior to others in corrosion resistance. The following table shows the extent of tunnel corrosion (crevice-type attack which forms a tunnel-like failure along the surface starting at the edge or crevice) which occurred after one year of exposure at a water depth of 2,340 feet.

AISI Type	Extent of Tunnel Attack
302	6 inches long
304	2 inches long
316	.5 inch long

It must be remembered that the corrosion of stainless steels is highly unpredictable and non-uniform. Some exposed areas will exhibit no corrosion while similarly exposed adjacent areas will exhibit severe attack. The corrosion on stainless steels in seawater is usually not evident for the first few months of exposure, but then proceeds at an increasing rate. Constant abrading action on stainless steels can actually improve their corrosion resistance; however, due to the construction of strength members, complete exposure like complete protection is impossible to achieve.

Due to the nature of the corrosive attack on stainless steel by seawater, its use in electro-mechanical cable is not recommended. Jacketing, unless 100 percent protection is assured, is ineffective in the mitigation of such attack.

For E-M cable strength members with required lifetimes in excess of ten years, alloys which do not corrode to any measurable extent in seawater are available. These alloys are: nearly all titanium alloys, nickel alloy Inconel 625*, and nickel alloy Hastelloy "C"*. These materials have been fabricated into wire ropes and their high cost may be justified for many operations.

Table II-3 is an outline of the relative strengths, corrosion resistances and costs of the wires described in this section.

*Trademarks of INCO and Cabot Corporation.

Table II-3. Properties of Metal Wires

Designation	Strength (Carbon Steel = 1)	Corrosion Performance	Cost (Carbon Steel = 1)
Carbon Steel	1.0	≈0.005 inch/year	1.0
Hot Dip Galvanized Carbon Steel	0.80	0 for ≈2 years, ≈0.005 inch/year thereafter	1.1
Hot Dip Aluminized Carbon Steel	0.75	0 for ≈2 years, ≈0.005 inch/year thereafter	1.2
Electrogalvanized Carbon Steel	1.0	0 for ≈6 months, ≈0.005 inch/year thereafter	1.2
Type 302 Stainless Steel	1.2	6 inches/year crevice attack	4.0
Type 304 Stainless Steel	1.2	2 inches/year crevice attack	4.0
Type 316 Stainless Steel	0.95	0.5 inch/year crevice attack	6.0
Titanium	1.3	No corrosion	20.0
Hastelloy "C"	0.8	No corrosion	40.0
Inconel 625	1.0	No corrosion	35.0

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III. ELECTRICAL CHARACTERISTICS OF ELECTRO-MECHANICAL SUBMARINE CABLES

From the standpoint of electrical characteristics, there are at least three basic types of E-M cable: the coaxial cable, the multi-conductor cable, and the single-conductor high-voltage/ampacity power cable. There is no one-to-one correspondence between application types and electrical types since E-M cables include all three electrical types, with the majority being either coaxial or single-conductor types. Suspended E-M cables, i.e., load-bearing cables suspended in the water column vertically, horizontally and anywhere between, include mainly coaxial and multi-conductor types. The high-power single-conductor type of cable is virtually excluded from water column E-M cables because there is, at present, no requirement for such cables, since the transfer of large amounts of power is limited almost entirely to land.

The most versatile signal-transmission cable is the coaxial type. The coaxial signal cable, as far as miles laid on the seafloor, far out-ranks the bottom-lying single-conductor power cable. In addition, practical types of E-M coaxial cable (i.e., having physical dimensions and mechanical characteristics which allow raising and lowering to deep ocean depths) can also carry power on the order of 100 KW simultaneously with high-frequency signals (bandwidth around 100 MHz). Because of the geometry of concentric conductors, the coaxial cable generally has better high-frequency characteristics than a multi-conductor or twisted-quad cable.

The signal-transmission characteristics of dry-jacket coaxial cable and dry-core shielded multi-conductor cable are not, in general, affected by the presence or absence of external armor, except insofar as the armor may prevent certain adverse mechanical effects such as axial twisting, small-radius bending, or physical damage to the jacketing material. E-M cables having an internal strength member concentric with a central conductor will, of course, have their electrical properties affected in that the low frequency (<100 Hz) resistance of the conductor is increased by the substitution of steel for copper.

Conductor Materials

Copper. Soft annealed copper (electrolytic, 99.99 percent pure) is used in the conducting members of the vast majority of E-M cables of the coaxial and multi-conductor types. Seafloor cables which are used primarily for multi-channel signal transmission also use copper in the conducting members. If the insulating materials has constituents, e.g., sulfur, which have corrosive effects on copper, the copper is coated with a thin layer of another metal or alloy; tin or lead/tin is commonly used for this purpose.

The main reasons for using copper in marine coaxial E-M cables is that these cables are used primarily for signal transmission, and copper provides the best combination of low cost and high conductivity—the latter being essential for maximum frequency bandwidth. In bottom-laid coaxial telephone cable, oxygen-free copper is used in the central conductor. Because a welded seam exists in this conductor, it is essential

that no oxide or gas pockets form under the heat of the welding operation which might weaken the structure of the conducting member. Also, oxygen-free copper can be obtained with high levels of ductility and conductivity.

Aluminum. Most high-voltage/ampacity ocean or river-bottom cables use copper conductors, although aluminum conductors have, at least in underground cables, been shown to be more cost effective where conductor weight is a critical factor.[1,2] Of approximately 260 high-pressure pipe-type cable systems, operating at or above 69 kilovolts and energized between the years 1959 and 1968, only about seven systems can be regarded as strictly underwater-cable types and, of these seven, only one uses aluminum conductors.[3] The one aluminum conductor system, in this group of seven, is a 2.5-mile river crossing.

In recent years serious attention has been given to the idea of using aluminum conductors in the majority of underground high-power systems; and presumably more and more high-power ocean cables will use aluminum in place of copper. The ampacities of aluminum-conductor and copper-conductor cable systems are compared in Table III-1.[4] Table III-2[2] lists the physical and electrical properties of several conductors, including copper and aluminum.

Sodium. A third metal, which shows considerable promise for use as the conductor in a high-power ocean cable, is sodium.[6,7,8] Its three major advantages are low density (0.97), high flexibility, and low cost (about half the cost of aluminum and one third the cost of copper, on a per-unit-weight basis[6,7]). Although sodium melts at relative low temperatures (97.5°C) and is extremely chemically active (explosively reactive to water if a large surface area of the metal is exposed), it has been found that polyethylene, a commonly used cable insulation, serves as an effective barrier to air and water while simultaneously providing good mechanical strength.[7] Finally, even though the conductivity of sodium is almost a third that of copper, copper is almost seven times as costly as sodium for equivalent ampacity.

Low Temperature Metals. The idea of operating high-power underground cable systems at low temperatures and even in the superconducting state has been examined in great detail in recent years.[1,9,10,11] There has been considerable progress since about 1962 in the development of high temperature superconductors* and superconducting transmission lines. However, there are still major problem areas requiring a considerable outlay of R&D funds before it will be possible to demonstrate the economic feasibility of superconducting power transmission systems.[1] Analysis[11] of a resistive cryogenic cable system (i.e., non-superconducting but operating at very low temperatures, e.g., between 20 and 77°K) has shown that such lines could compete on a cost basis with conventional oil-paper pipe-type cables rated in excess of 1000 megawatts. Practical superconducting ocean-cable systems would probably use superconducting alloys of

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*Highest superconducting temperature is slightly above 20°K.[12] The alloy is niobium/aluminum/germanium.

Table III-1. Ampacities of Aluminum and Copper Cables in Underground Ducts, 20°C Earth Temperature[4]

Metal	Size (Mcm)	Cross-Section Area (in^2)	Ampacity* (amperes) 3 Conductors per Duct	
			5 kV	35 kV
Aluminum	250	0.196	264	274
	500	0.293	397	406
	1000	0.784	588	595
Copper	250	0.196	338	351
	500	0.392	503	516
	1000	0.784	720	736

* 75 percent load factor, compacted strands (non-circular cross-section).

Table III-2. Properties of Conductor Materials[2]

	Specific Gravity	Tensile Strength psi	Elongation %	Resistivity microhm-cm[3]	Conductivity %	Applications Requiring	Remarks
				Pure Metals			
Aluminum	2.7	35,000	30-45	2.8264	67	Minimal Weight	Low Modulus, High Coefficient of Expansion, Nick Sensitive
Copper	8.99	35,000	10-35	1.724	100	Normal Service Installations	Excellent General Properties, Economical
Molybdenum	10.2	100,000		5.7	30	Flexibility Strength	Strength Member for Stranded Conductor
Sodium	0.97	Virtually that of the insulation	14-43	4.88	35	Burial, Messenger, Supported Aerial Wires	Low Cost, Presents Sodium Fire Hazard
				Copper Alloys			
Beryllium Copper	8.23	58,000-200,000	1-35	1.19	90	Strength, Flexibility, Noncorrosive	Relatively Expensive
Bronze (Phosphorus	8.89	40,000-60,000	3-47	3.6	48	Severe Service, Strength, Flexibility	Rapid Flexing Recovery
Cadmium Copper	8.89	38,000-90,000	1.5-4	2-4	40-85	High Strength and Temperature	
Cadmium Chromium Copper		60,000-110,000	1-8	1.9-2.2	80-90	High Strength, Temperature, Flexibility and Conductivity	Easily Fabricated, Compatible with Fluorocarbon Insulations
Chromium Copper	8.89	41,000-90,000	1.5-2.8	2-3	58-86	Flexibility, Strength	
Tellurium Copper	6.25-8.89	40,000+				Strength, Corrosive Resistance, High Temperature	Availability Restricted
Zirconium Copper	9.27	56,000	25	1.9	90	Strength, Flexibility	Noncorrosive
				Clad			
Copper Covered Steel	7.8	100,000-200,000		4.5-5.5	30-40	Strength	
Silver/Nickel/Copper	9.0	150,000				Strength, High Temperature	Noncorrosive
Copper Aluminum	2.7	38,000	1-10			Minimal Weight	Low Strength, Low Flex Life, Susceptible to Galvanic Corrosion
				Coatings			
Tin	7.3	4,000-5,000		11.5	15.0	Corrosion Protection	Excellent Solderability
Lead	11.34	2,600 3,300		22.5	7.8	Corrosion Protection	Nominal Solderability
Zinc	7.2	7,000-30,000		5.7	30.0	Corrosion Protection	
Silver	10.6	42,000		1.64	105.0	High Temperature	Expensive
Gold	19.3	18,000-32,000		2.19	73.0	Corrosion Protection	Very Expensive

the niobium/metal type. Resistive cryogenic submarine cables would probably use aluminum, mainly because of the cost and weight advantages of aluminum.

Dielectric Materials (Summarized in Table III-3)

The most important function of a dielectric material in an E-M cable is the isolation of current-carrying elements. Most of the dielectric materials used in cables in the ocean and their properties are listed in Table III-3; they are either solid or liquid types, with most cables using solid dielectrics of the plastic or elastomer types. The only submarine cables which use liquid dielectrics are high-power seafloor cable systems such as pipe-type systems and hollow-conductor cables. Actually, the liquids in pipe and hollow-conductor systems are not used as dielectrics to isolate conductors since in both types of cable systems a solid dielectric is used. The oil is used to improve the thermal characteristics of the system and enhance the performance of the solid dielectric. In recent years, compressed gas insulation has been used in underground high-power cable systems[1] but, as yet, gas has not been used as the dielectric in ocean cable systems. In a gas-insulated system solid dielectric spacers are used to isolate the conductor from the pipe which contains the gas.

Polyethylene. Polyethylene has a good balance of electrical properties, mechanical properties, and cost. Its relatively low dielectric constant combined with its suitability for thick-walled extrusions, make it one of the best dielectrics yet developed for long-distance coaxial telephone cables.[13,14] Natural (low-density) polyethylene has a specific gravity around 0.9 and is suitable for virtually all types of E-M coaxial cables. Natural polyethylene has a moderate dielectric strength so that power up to above 5000 volts can be carried on most ocean telephone coaxial cables. Cross-linked polyethylene[2,15,16] has a high dielectric strength and is used in high-voltage/high-power single-conductor cables to separate the conductor cables from the electrical shield.

The moisture resistance and low temperature performance of polyethylene is superior to those of other cable insulating materials. The disadvantages of natural polyethylene are flammability, stiffness, and a maximum operating temperature of 80°C. Cross-linking will raise the continuous operating temperature to around 150°C. A recently tested single-conductor power cable[17] uses cross-linked polyethylene separated from the conductor by a semi-conducting tape soaked in silicone oil. The presence of the liquid allows smaller insulation thickness and hence improved flexibility (smaller bending radius).

Polypropylene. Polypropylene is superior to natural polyethylene with respect to mechanical strength and dielectric strength; however, polypropylene constructions are limited to relatively thin-walled extrusions.[2] This plastic is also susceptible to copper poisoning which can be prevented by proper tinning of the copper.

Table III-3. Properties of Insulation Materials[2]

Material	Specific Gravity	Tensile Strength psi	Elongation %	Tear Strength lb/in. Thickness	Abrasion Resistance	Hardness Shore "A"	Brittleness Temperature °C	Cold Flow Resistance
Buna N	0.96-1.02	500-900	450-700	15	Good	10-100	-18 to -65	Excellent
Buna S	0.94	2500-3500	400-800	15	Good	35-100	-80	Excellent
Butyl	0.91	2500-3000	750-900	Fair	Good	15-75	-80	Excellent
Ionomer (Surlyn)(1)	0.96	3500-5500	400	Good	Good	60-65	-105	Good
Polyethylene								
Standard	0.95	2000	400	Fair	Fair	40	-50	Poor
Low Molecular Weight	0.910-0.925	1000-2300	30-450	Fair	Fair	40	-50	Poor
Medium Molecular Weight	0.926-0.940	1200-3500	100-600	Fair	Good	40	-50	Poor
High Molecular Weight	0.941-0.965	3100-5500	15-100	Good	Good	60-95	-60	Fair
Cross-Linked (Vulkene)	1.30	1850	300	Excellent	Very Good	-	-55	Good
Ethylene-Propylene	0.861	800-3000	200	Good	Fair	65-95	-60	Good
Polypropylene	0.90-0.91	4300-5700	700	Good	Good	-	-50	Good
Polysulphone	1.25	10,200	50-100	30	Very Good	100	-55	Good
Silicone Rubber	1.1-1.5	750-1200	120-275	Poor	Poor	-	-80	Good
Polyvinylchloride	1.2-1.7	1000-3500	200-400	45	Good	35-95	-30	Good

Table III-3. Properties of Insulation Materials[2] (continued)

Material	Bondability	Moisture Resistance	Volume Resistivity ohm-cm	Dielectric Strength volts/mil	Dielectric Constant 1 KHz	Power Factor %	Continuous Service Temperature ^{o}C
Buna	Good	Excellent	10^{10}	500	13.0	5.5	150
Buna S	Good	15 $mg/in.^2$ 168 hr at $70^{o}C$	10^{15}	500	2.9	3.0	125
Butyl	Good	8 $mg/in.^2$ 168 hr at $70^{o}C$	10^{17}	600	2.1-2.4	3.0	75
Ionomer (Surlyn)(1)	Good	1.5%-2.5% weight gain	10^{17}	1100	3.36	0.1	75
Polyethylene							
Standard	Good	Nil	10^{16}	600	2.2-2.5	0.03	-60 to 80
Low Molecular Weight	Good	Nil	10^{16}	500	2.2-2.5	0.03	-60 to 80
Medium Molecular Weight	Good	Nil	10^{16}	600	2.2-2.5	0.02	-60 to 80
High Molecular Weight	Good	Nil	10^{15}	600	2.2-2.5	0.02	-60 to 80
Cross-Linked (Vulkene)	Good	3 $mg/in.^2$ 168 hr at $70^{o}C$	10^{15}	600	2.5	1.8	-50 to 125
Ethylene-Propylene	Treatable	Nil	10^{17}	900	3.3	0.65	-40 to 150
Polypropylene	Good	Nil	$5x10^{15}$	650	2.2	0.03	-40 to 80
Polysulphone	Good	0.22%, 24 hr	10^{16}	400	3.3	0.1	-50 to 150
Silicone Rubber	Excellent	3.8% weight gain	10^{14}	100-600	3.2	0.1-1.0	-60 to 200
Polyvinylchloride	Good	1%-2% weight gain	$10^{11}-10^{14}$	500	5.0	9.0	-20 to 100

(1)Trademark of E. I. du Pont de Nemours and Company.

Teflon (Polytetrafluoroethylene). Teflon is the most thermally stable and chemically resistant of all dielectrics. Its temperature range is -90°C to 250°C and it is in wide use as a wire insulation where there is a problem of overheating at solder terminations. Its abrasion and cut-through resistance are not as good as those of cross-linked polyethylene and polypropylene. Also, it is not suitable for high-voltage applications—because of poor corona resistance. For these reasons, and the fact that its cost is relatively high, teflon is used only in special electro-mechanical coaxial or multi-conductor cables where chemical and thermal stability is important. Its dielectric constant is lower than polyethylene and most other commonly used dielectrics, so that it is particularly useful in ocean experiments where low signal attenuation is vital.

Silicone Rubber. Silicone rubber is a good, flexible, high-temperature elastomeric insulator and is used mainly in multi-conductor electromechanical cables where a combination of relatively high voltage and flexibility is desirable. Its dielectric constant is around 3.2 and, hence, it is not particularly suitable for high frequency signal-transmission cables.

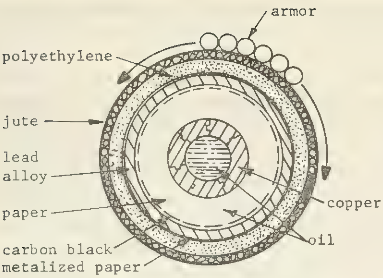
EPR (Ethylene Propylene Rubber). EPR shows considerable promise as a dielectric in high-power ocean cable systems because of its very high resistance to corona.[18] A number of EPR cables have been manufactured for voltages up to 60 kV. It has superior thermal stability relative to polyethylene and rubber.

SF_6. SF_6 (Sulfur Hexafluoride) is a gaseous dielectric which offers advantages over other dielectrics used in high-voltage/high-ampacity power cable systems.[19] The advantages of gas insulation are its excellent heat-transfer characteristics, its low dielectric constant (unity at all frequencies). Compressed-gas-insulated cables are being installed in underground distribution systems, and it is expected that as pipe technology improves, such cables will be utilized in ocean power distribution systems.

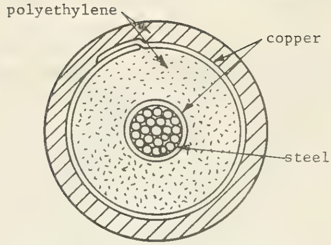
Design of Conductor Systems

Most cables used in the ocean have conductor systems which fall into one of the three basic categories mentioned previously: coaxial, multi-conductor, and single-conductor high-power cable. This classification scheme is not complete since many E-M cables are hybrid types which may have more than one coaxial cable together with single conductors or may contain a large collection of insulated conductors which are grouped in twisted pairs or quads. Also, an E-M cable which does not fall into the basic classification scheme is the medium power three-phase system, consisting of three or four heavy conductors in the same cable.

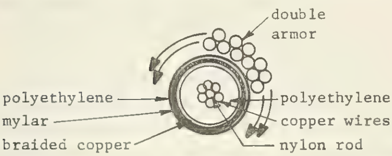
Figure III-1 shows schematics of the cross-sections of typical conductor systems used in E-M and ocean cables. The two systems which lend themselves to relatively simple mathematical analysis are the single-conductor cable and the coaxial cable. It is extremely difficult, if not impossible to mathematically construct the electromagnetic fields of the



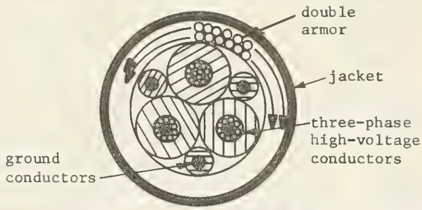
SINGLE-CONDUCTOR OCEAN CABLE
(Lead Sheath Diameter, 2.1 inches)



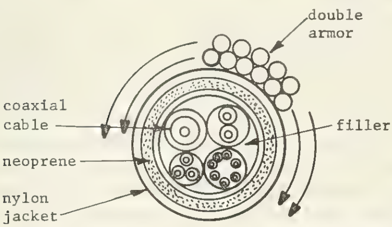
COAXIAL ARMORLESS OCEAN CABLE
(Polyethylene Jacket Diameter, 1.25 inches)



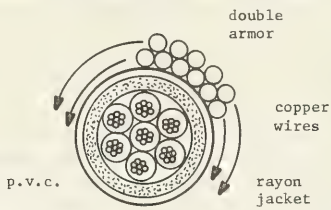
COAXIAL ELECTROMECHANICAL CABLE
(Polyethylene Jacket Diameter, 0.405 inch)



THREE-CONDUCTOR ELECTROMECHANICAL CABLE
(Jacket Diameter, 1.80 inches)



COAXIAL/MULTICONDUCTOR ELECTROMECHANICAL CABLE
(Nylon Jacket Diameter, 0.647 inch)



MULTICONDUCTOR ELECTROMECHANICAL CABLE
(Rayon Jacket Diameter, 0.187 inch)

Figure III-1. Cross section schematics of conductor systems for submarine cables.

multi-conductor cables, and one must usually be satisfied with a lumped circuit analytical approach using experimentally derived electrical parameters.

Single-Conductor Cable. Most E-M cables have at least two conductors. Single-conductor cables mostly include seafloor telegraph cables and seafloor power cables. A detailed discussion of the electromagnetic and lumped-circuit characteristics of ocean power cables is beyond the scope of this report. However, it should be mentioned that an important parameter in the single-conductor power cable is capacitance-to-ground, which is the reason that AC-powered transmission over great distance is not cost effective beyond a certain point, because of the per-cycle energy required to charge capacitance. This is true of all single-conductor and multi-conductor cable systems. For this reason, considerable development effort is being devoted to AC-to-DC high-voltage conversion techniques. AC is required to convert generator voltage to high voltage; high voltage is required to minimize I^2R losses over great distances; and DC is required to minimize energy losses due to capacitive transmission systems.

The simplest design of a single-conductor ocean power cable is an insulated copper rod pipe filled with oil maintained at pressures between 150 psi and 500 psi. Two separate pipe/conductor lines would be used for a single-phase power system and three separate lines for a three-phase system. Voltage is usually 69 kV or greater, and power ratings are on the order of 100 MVA and above. The insulated conductor is usually shielded (in the case of non-metallic pipes) with lead-alloy or aluminum sheaths and sometimes metallized or carbon-black tape.

Another type of single-conductor ocean power cable, which uses a hollow conductor filled with oil, is stranded or contains openings which allow the oil to penetrate through into the surrounding insulation. An example of the hollow-conductor oil-filled power-cable system is the seven-cable Long Island Sound submarine cable interconnection.[20] Rated voltage and nominal power for this system are 138 kV and 300 MVA, respectively. The single-conductor cables in this system could be regarded as E-M types in that each cable has a layer of stranded steel armor, giving the cable a weight of around 8 pounds/foot and a breaking strength of approximately 50,000 pounds. The maximum depth for the cable is 200 feet and the undersea distance is about 11 nautical miles. The cable can be manufactured in splice-free lengths up to 35 nautical miles. For the main crossing in deeper water, the cables are exposed to the sea and lie directly on the bottom.

Coaxial Cable. For wide-band long-distance signal transmission the coaxial system is the most efficient. It is basically a circular-cross-section wave guide with an axial conductor. The central conductor eliminates the main disadvantage of the hollow-tube transmission line by allowing the existence of a principal mode and, hence, propagation of signals at all frequencies. In the hollow tube, only wavelengths on the order of the tube diameter, or less, are allowed; hence, power frequencies and a rather wide band of signal frequencies would be excluded in a hollowed tube line of reasonable diameter.

The coaxial transmission line confines the electromagnetic field to its interior, as does the hollow-tube line, and therefore eliminates interference with external circuits at high frequencies. At low frequencies the skin depth may exceed the thickness of the outer conductor, causing not only energy loss but also cross talk, i.e., interference caused by currents induced in communication lines through shields. For frequencies over 10 kHz, the skin depth is less than about 0.01 inch. Therefore, for coaxial cables in which carrier frequencies lie in the band above 100 kHz—which is the case for transatlantic telephone lines—the thickness of the outer conductor need, ideally, be only greater than 0.01 inch.

Coaxial cables, like all transmission lines, have four basic electrical parameters which, in turn, determine the four secondary electrical parameters commonly used to characterize the cable. The basic parameters are the per-unit-length quantities, R, L, G, and C (resistance, inductance, conductance, and capacitance); the parameters which caracterize the cable are attenuation, phase shift, characteristic impedance, and propagation velocity.

The two most important secondary electrical parameters are the attenuation and the characteristic impedance. Attenuation gives the cable loss in dB per unit length and must be considered in designing the cable. Characteristic impedance must be known in order to design terminal and repeater equipment such that optimum impedance matching is achieved. The phase shift and the propagation velocity are related through the frequency; velocity is the speed at which a signal, a pulse, for example, travels along the coaxial cable. Practical lower and upper limits of velocity are about 4000 miles/second and 100,000 miles/second, respectively. The characteristic impedance is the impedance measured at the input between the central and outer conductor of an infinitely long cable. For a cable of finite length, impredance is experimentally determined by measuring the input impedance, first with the far end open and then with the far end shortened.

Dielectric sizing may require extremely tight design tolerance because positive and negative diameter excursions of a certain magnitude would not be sufficiently self-cancelling to hold the net attentuation to a low enough value. For example, in the manufacture of SD telephone cable—a bottom-lying armorless submarine cable[13,14] having a dielectric O.D. of 1 inch—control of the extrusion process is not able to hold diameter variations below about ±0.005 inch. A supplementary sizing operation is required (involving actual cutting of the polyethylene dielectric) to hold diameter variations under ±0.0001 inch.

Direct measurement of R, L, G, and C, under different conditions of temperature and pressure (controlled in laboratory tests), yield experimental temperature and pressure coefficients which, then, can be used to find the effect on attenuation. For the SD ocean cable mentioned earlier, it turns out that the temperature coefficient accounts for over 75 percent of the effect on attenuation. Pressure change causes the pressure coefficient to affect over 50 percent of the attenuation.

The characteristic impedance of most coaxial-electro-mechanical submarine cables lies between about 40 and 70 ohms. Besides being essential to the design of terminal and repeater equipment, knowledge of the

characteristic impedance is important in establishing design criteria for splicing coaxial cable. In general, an impedance or admittance discontinuity in a signal transmission cable will cause reflection of energy and, hence, loss.

In the case of relatively short-distance E-M cables (surface-to-bottom types) reasonable care in soldering/welding electrical conductors and molding/extruding the dielectric will insure that signal losses are under 1 percent. Only the grossest negligence in splicing will cause reflection losses to approach 50 percent. An inexperienced (but still conscientious) splicer could, by soldering on improperly cleaned surfaces or at too low a temperature, produce a 2-ohm series resistance in the central conductor of the coaxial cable. A large admittance could be generated by allowing a thin disc-shaped pocket to remain in the dielectric and fill with seawater.

In the manufacture of S-series submarine telephone cable[14] it sometimes becomes necessary to splice the armorless coaxial line because of damage in the central conductor. Copper-plated sleeves, more than twice the diameter of the central conductor, are inserted at points where the strand in the central strength member may have been damaged or where more than 2 inches of copper is missing. Since these repairs constitute potential weak points in the cable and produce a certain amount of signal reflection (although well below 1 percent), not more than two splices are permitted within any 20-nautical mile section of cable. Restoration of the polyethylene dielectric is done by extrusion molding. The completed joint is x-rayed to check for inclusions, voids, and eccentricity.

For most of its length a deep-ocean S-series coaxial telephone cable does not have to be shielded against external signals and noise. However, on passing through shallow water at the shore ends, electrical shielding is provided in the form of high-permeability steel tape and, as discussed elsewhere in this report, various types of armoring are also provided. Shields of high-permeability steel tape actually function as magnetic shields and reduce the inductive coupling to the internal conductors. The magnetic shield diverts the disturbing field around the conductors by providing a low-reluctant path; also, eddy currents are set up in the shield which generate opposing fields to the external field.

The latest S-series submarine cable to be manufactured in large quantity is the SF cable.[21,22] It has a larger dielectric O.D. than the SD cable which, in turn, yields a bandwidth about six times that of the SD cable. Table III-4 lists the pertinent physical, electrical, and system characteristics of the SB, SD, and SF cables. As of this writing, the SG cable is on the drawing board.

Multi-Conductor Cables. Multi-conductor E-M cables are used for instrumentation, control, and signal transmission. A control and instrumentation cable may have as many as 59 separate conductors contained within a circular cross-section area of 1.6 inches diameter. A cable of this type would be capable of carrying voltages up to about 500 volts between single-wire conductors and up to about 1000 volts on separate coaxial cables contained in the same 1.6-inch diameter area. These small diameter coaxial cables have larger resistance and capacitance per foot than coaxial ocean telephone cables and, hence, larger attenuation.

Table III-4. Electrical Characteristics of S-Series Submarine Coaxial Telephone Cable[13,21]

	SB	SD	SF
Cable O.D.	0.620 inch*	1.00 inch	1.50 inch
Cable Length	2200 nautical miles	3500 nautical miles	4000 nautical miles
Strength Member	external armor	steel strands in center	steel strands in center
Repeater Spacing	38.7 nautical miles	20 nautical miles	10 nautical miles
Number of Channels	48**	128**	720**
Maximum Signal Frequency	164 kHz	1.1 MHz	5.9 MHz
Terminal DC Voltage for Repeater Power		5500 volts	3500 volts
DC Current for Repeater Power		390 ma	136 ma

* Two cables: one for each direction of transmission.
** Channel width = 3 kHz (frequency multiplexing).

Attenuation is typically around 7 dB/nautical mile at 100 kHz, as compared to about 1 dB/nautical mile for SF coaxial cable. However, because of the relatively short lengths of the multi-conductor E-M cable used in ocean operations (1 nautical mile), high resolution TV signals can be transmitted without repeaters at carrier frequencies around 100 MHz.

The main reason for using a multi-conductor cable of this kind—rather than a single small-diameter coaxial cable with all signals multiplexed on the one coaxial cable—is to insure precision of measurement in deep sea experiments in which errors introduced by multiplexing cannot be tolerated. Also, if conductors in the multi-conductor cable are grouped into twisted pairs or quads, the effect of extraneous signals is less than it would be for a coaxial line.

An example of a multi-conductor E-M submarine cable is the 10,000-foot 10-conductor signal cable used in the Oceanic Telescope Engineering Program.[23] This double-armored plastic-jacketed cable is about 1.5 inches O.D. and was used in a long-term horizontal sensor array for measuring temperature and pressure variations at 630 meters depth. Under the armor a neoprene layer encloses the insulated conductors, providing a double seal against seawater penetration to the conductors. Another example of a multi-conductor E-M cable is the cable used for load handling, power, and signal transmission in the DOTIPOS system[24] at NCEL. This cable is double-armored of 1.116-inches O.D. made up of one coaxial cable for command and data telemetry, a second coaxial cable for TV signals, and two twisted pairs of #12 AWG copper for transmission of 2400 V. 60 Hz power. The length of the cable is 8,000 feet.

Most of the quad-type ocean cables manufactured by Simplex are of the wet-core construction.[5] The seawater actually penetrates the cable into the primary insulation of each conductor such that the water forms and electrostatic shield around each conductor. A single-quad cable, for example, uses four #18 AWG copper wires, each having an insulation diameter of 0.13 inch, and each wire having a DC resistance of 6.2 ohms per 1,000 feet. The capacitance of a pair of conductors is 0.017 microfarad/1,000 feet, and the maximum working voltage about 600 volts. A wet-core quad of 0.45-inch diameter will have the same capacitance and working voltage but a resistance of 3.2 ohms per 1,000 feet.

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IV. HANDLING OF ELECTRO-MECHANICAL CABLES

Cable handling includes shipping, loading, deployment and retrieval. Improper handling has caused many failures of cable systems resulting in loss of substantial time and money. One of the major problems is the formation of kinks. Although, in most cases, cable deployment is carefully planned and prepared, electrical and mechanical failures still occur due to lack of knowledge of proper handling. Literature on cable handling is not readily available; therefore, the novice engineer learns proper handling techniques through mistakes. Some useful experiences have been documented within the transocean telephone cable laying and the offshore petroleum industries. But this valuable knowledge is proprietary information and, consequently, is not generally available.

Cable manufacturers can only offer limited information on handling techniques. Handling information on new cables such as torque-balanced armored cables is virtually nonexistent. As ocean technology moves with more complicated cable systems into deeper water, the need for reliable underwater cable construction increases greatly. Proper cable handling techniques must be developed and documented as soon as possible to answer this requirement. This section provides a general background of the handling procedures, the current understandings, and the future needs.

Cable Handling Procedure

Cable handling is discussed below under three topic headings: cable transport, ship loading, and cable deployment and retrieval. During shipping and loading, the tension in the cable is small, and its behavior depends on the rotation and torque caused by external movements. Whereas for paying out and retrieval, tension-induced rotation and torque in the cable are the important factors. In general, shipping and loading are easier than the cable laying and retrieving.

Cable Transport. Cables are manufactured in several stages. At each stage a cable is fed into a machine or a series of machines and then taken up on a reel. Later it is transported to another machine and the next stage. After the cable is fabricated it is either wound in a shipping reel or stowed in a pan. This may require transferring the cable from the factory reel to a layer shipping reel or pan by means of a line puller. The reel or pan is then lifted on to a flatbed truck or a railroad car for shipment. Several cable manufacturers have facilities for directly loading cable ships or barges. Cable reels as large as 15 feet in diameter and weighing 50 tons can be shipped by truck and railroad car.

If the cable assembly is to contain in-line packages such as hydrophones or engineering sensors, it is transported to an assembly plant where the cable is streamed out, cut and spliced to include the in-line packages. The cable is then shipped to the loading site in one of two ways. It can be wound on a three-flanged reel and shipped by flatbed truck or rail. The third flange is used to separate the cable and the packages for smoother winding. Or, it can be coiled on a flatbed deck for shipment.

Ship Loading. The loading of the ship is not difficult if the shipping reel fits the cable paying machine. The reel can be simply lifted by a heavy crane and positioned on the shipboard cable winch. If the shipping reel is not to be used on the winch, the cable may be transferred from the shipping reel to the ship winch storage drum. If in-line packages are present, a third flange is installed in the winch drum to separate the cable from the packages. If the cable assembly is unloaded from a pan to the ship winch drum, the procedure is similar. However, more often, the cable is unloaded from a shipping pan and stored in the ship's tank. Sometimes a reel of cable is loaded onto a tank through the ship winch. The shipboard cable handling winch may consist of a couple of bull wheels, or a traction drum with fleeting knives, a linear puller is equipped with some cable ships for loading and deployment. Sheaves with large "V" shaped grooves and chutes have been used for guiding the cable during the loading process. Formation of kinks have been observed when double-armored cable was being transferred from a flatbed truck to the ship's tank.

Cable Deployment and Retrieval. During deployment the cable is taken out of the tank or the storage drum, through a puller or traction winch, over a large sheave or a chute, and into the sea. During water column suspension, the weight of the cable and the payload generates high static tension in the cable. The ship motion causes large dynamic fluctuations of the line tension. The cable tension is usually monitored by a dynamometer.

For bottom cable laying, the ship steams at a predetermined speed while cable is being payed out at the same rate. If the cable is being laid on a sloping seafloor, proper adjustment of payout speed is necessary for minimum tension at the lower end. If the cable does not reach the shore, the cable is cut and lowered to the seafloor. It is later retrieved and spliced to another cable. Kinks have been found in armored cable taken out of the ship tank for deployment. Kinks also exist in cables after they are lowered to seafloor.

A cable system may be retrieved for splicing, repairing and storage. Usually, it is recovered and stored on a drum or in a tank. Some operations may require that the cable be suspended below the ship or barge for an extended period of time. Only a small percentage of the cable layed on the seafloor has been retrieved. The cable retrieved often has had kinks.

Deployment Discussion

A review of many unsuccessful deployments of underwater cable systems was made. It is concluded that many handling errors could have been avoided if there had been a better understanding of the cable rotational properties, the handling and storage hardware, and the cable loadings during deployment. Through interviews with telephone cable laying companies, offshore service companies, cable manufacturers, and Navy cable users, and through a literature search, valuable information was accumulated and is summarized in this section.

Cable Rotational Properties. Because a cable is constructed with helically-wound preformed wires, it rotates not only under externally applied torsion but also under tension. The resistance to such loadings varies, depending on the size, material and mechanical design of the cable. The amount of torque-induced rotation is a measure of the torsional stiffness, which is an important factor affecting the formation of kinks in a slack cable. Cables having small torsional stiffness tend to twist under torque and are easy to handle during coiling. Cables with large torsional stiffness have high resistance to rotation and would rather deform into a loop than rotate about its longitudinal axis. Another characteristic of stiff cables is the ability to spread torque throughout its length, even when in coils. This redistribution of torque within the tank may be responsible for the formation of kinks when the cable is payed out.

During deployment, the controlling factor is the tension-induced rotation. Cable rotation occurs when the cable and payload are suspended freely in the water. When the payload lands on the seafloor, slack occurs in the cable. This reduction in tension causes the cable to untwist. However, since both ends of the cable are now unable to rotate, the cable deforms and twists into loops. As tension is reapplied, the twisted loops form kinks. Because a slack line is necessary to form these twisted loops, maintaining a small cable tension (about equal to the weight of the wire) is essential to prevent kink formation. Another method of avoiding kink formation is to use twist-free cable. To provide satisfactory results, the cable should be designed so that it will not rotate under the expected range of tensions.

There are three types of cables that can be considered to be nearly twist free. The first is a double-armored cable designed so that the two layers of armor produce an equal but opposite torque under a selected working tension. The second type has a central strength cable which is a torque-balanced wire rope. The torque produced by each individual strand is balanced by the torque produced by the lay of the rope. The last type of design uses the same principle of torque-balanced wire rope, but the torque-balancing strands are now laid outside the electrical core as armor. Some manufacturers advertise cables that rotate only 0.1 degree per foot at 50 percent of the breaking strength. While torque compensation is advantageous during cable deployment, the contrary is true during shipping and loading. Such cable is difficult to handle during coiling and uncoiling in a tank.

Equipment and Hardware

Cable Storage Equipment. A special feature of the cable tank is its large volume; for example, the largest tank on C/S LONG LINES can store 2,000 nautical miles of 1 1/4-inch-diameter deep-sea armorless cable. The minimum coil diameter is 10 feet. For each coil of cable in the tank, a rotation of 360 degrees about the longitudinal axis is added to the cable. The tank is effective for long lengths of armorless transoceanic telephone cable (SD type) because the cable has a small central strength member which provides little resistance to rotation. The cable packs nicely in the tank without kinks. As the cable is payed out from the

tank, the rotation is released. Any residual rotation is easily absorbed by the cable.

On the other hand, a double-armored cable may possess enough rotational resistance that during loading the cable will not lay flatly on the bottom of the tank. As the cable is forced down to form a fake, the rotation creeps to the adjoining coils. When the cable is taken out of the tank, another rotation redistribution takes place. Sometimes a local concentration of rotation occurs, and results in the formation of kinks which cannot be relieved without cutting and splicing. This phenomenon resembles the tangling of a long length of cheap grade garden hose. Another factor which contributes to kinking is the coiling procedure. For tight packing, it is necessary to coil the cable from the tank core to the wall and back to the core again. When the cable is being payed out from the tank wall toward the center core, the double-armored cable has a great tendency to stick to the next coil of cable; both are pulled up together. The result is a kink.

Bulky in-line packages often cause handling problems. Their large circumferential frictional resistance stops the propagation creeping cable rotation causing local concentration of torque and encouraging kink formation. The cable section with such packages should be stored in a separate box adjacent to the tank. The tank is a good storage vessel provided the cable can satisfactorily tolerate the amount of rotation imposed on it during loading. The above comments about cable tanks also apply to the coiling of cables into tubes, pans, and flatbeds.

Cable reels may be mounted on a horizontal shaft or a vertical shaft. The horizontal reel is most common. If a traction winch or linear puller is not to be used, the cable is generally wound on the drum in tension for tight packing so that during payout the high tension cable from load will not cut into the soft layer of cable causing severe cable damage. The advantage of using a reel is that no rotation is induced during loading and payout. The cable is torque-free coming out of the drum if it was loaded torque-free. The main disadvantage of a reel is probably its limitation on handling long length large-diameter (over 2 inches) cable. Large drums and winches are available off the shelf and have been used by the mining industry. However, the space and weight requirements for the winch system and the power plant are a problem for shipboard use. The weight of the cable and winch on the deck will affect the stability of a small ship.

Another serious disadvantage of a reel is the difficulty encountered when in-line packages are used, as would be the case with most undersea sensor array systems. The winding of the cable with in-line packages is difficult to avoid. For better winding, a third flange may be inserted in the drum to divide the cable from the packages. However, cross laying of the cable still cannot be totally avoided. In some systems, in-line hard wire connected packages may be replaced by quick-attachment inductively connected packages. The packages can be attached around the cable just before it enters the water. For large size double-armored cables with long lay length, the minimum bend radius has to be so large that winch size required becomes too large to be practical. In this case, a drum on a vertical axis may be used. However, such an arrangement has a disadvantage; cable turns frequently drop toward the lower flange causing

a serious problem during payout operations. In-line packages would increase this problem. A vertical drum with a third flange has not been used for cable handling. A vertical level wind with proper tensioning may alleviate this problem. For a flexible armored cable of relatively short length, a reel should be used for storage and handling on board a ship.

Cable Payout Equipment. The major differences between a cable chute and cable sheave are cost and rotational resistance. To reduce bending fatigue, a tensioned cable should be passed over a curved surface of adequate radius. A rule of thumb is that the chute sheave radius should be 400 times the radius of the outer armor wire or 40 times the cable radius, whichever is larger. In general, the cost of a cable chute is cheaper than a large sheave of the same radius. The sheave also requires more deck space. A cable can rotate more freely within a wide chute than in a narrow groove of a sheave. A torque cannot be transferred through a cable over a sheave. When a nontorque-balanced cable is stretched between two sheaves, a torque is produced in the cable. Because there is no rotation in this section, the torque will not be relieved by spreading through the remainder of the cable. However, if one of the sheaves is replaced by a chute, the cable will rotate in the chute and reduce the torque concentration.

When a large V-groove sheave is used, often the cable leaving the sheave touches the sheave flange. If it touches the right flange as it is payed out, a clockwise torque will be applied to the cable by friction, causing the cable to rotate clockwise and to clumb up the flange. This is not desirable as it causes local erosion of the sheave and induces in-line torque. The key to this problem is to keep the cable clear of the sheave flanges.

A cable chute is adequate for handling smooth armorless deep-sea telephone cable which is deployed with relatively low cable tension because the chute is kept lubricated, only 90 degrees of arc is necessary and the cable is passed over the chute only once. It has been shown that after periods of operation neither the chute nor the cable showed any substantial wear. A sheave is recommended for handling bare armored cables in high tension.

Cable Pulling Machines. A traction drum can provide higher pulling force and costs less compared to a linear puller. But if the drum uses fleeting knives to keep the cable in place, a torque and twist is induced in the cable. An equal amount of rotation will develop in the cable on each side of the winch. This rotation and torque will build up and cause kinks, especially during the tank loading when line tension is small. Such torque will not occur for grooved traction drums because the cable is not forced to roll across the drum.

A linear puller can handle cable with in-line packages up to 14 inches in diameter and 20 feet long and provide up to 20,000 pounds of pull. This system is too large for ships of opportunity. Only specialized cable ships are equipped with such handling equipments.

Hydraulic control and motion compensation devices are desirable to

maintain a controlled tension in cables during deployment. These features also reduce greatly the dynamic tensions in the cable.

Electrical Ingress Devices. If the electrical circuit is required to be monitored during the cable deployment, slip rings are generally used on the cable spool. For multi-conductor and coaxial cable, the complexity of such slip rings increases and reliability decreases. A "transfer drum" design in the cable spool eliminates the use of slip rings. The design consists of two parallel drums revolving about each other inside the cable spool. One end of a drum connects to one spool shaft while one end of the other drum connects to the cable spool. Electrical cable comes in through the shaft, wraps on one drum in one direction and on the other drum in the other direction and, finally, connects to the electrical-mechanical cable on the cable spool. As the cable is being payed out, the internal transfer drums transfer the electrical cable from one drum to another allowing electrical continuity without the use of a slip ring.

The disadvantages of such a design are additional resistance due to the increase in cable length and the fatigue strain induced to the cable conductors during the transferring from one drum to another.

Surface Platform. Towed barges have been used in relatively shallow water by the offshore industry for laying power and communication cables. In high seas, it becomes difficult to maintain a course. Huge cable ships are used in transocean telephone cable laying. The C/S LONG LINE is 550 feet long and was built to lay armorless SD cable only. No particular difficulties have been reported. A dynamically positioned ship NAUBUC was used in cable laying operations and provided automatic control of the course. The system worked successfully in maintaining course but the lateral thrusters caused severe rolling of the ship.

Flotation Packages. For deep ocean deployments it is generally required that a suspended cable be neutrally buoyant. Spherical buoys have been attached manually to the cable during the paying out phase. Fast snap-on slamps and preformed wires have been used to fasten the buoys. Even so, the process is time-consuming and as the cable rotates in the water the buoys may be worked loose. The problem may be eliminated by the development of neutrally buoyant cables or quickly attached buoyant jackets. Development work is currently being conducted by the Navy on "buoyant" working and structural cables.

Inspection and Protection

After cable is laid on the seafloor in shallow water the general practice is to check the electrical characteristics. If the cable does not perform properly divers are sent down to inspect the cable. Usually the damaged location is found, retrieved and repaired. In deep water the inspection of cables either laid on the seafloor or suspended in the water column becomes a difficult task. Small working submersibles are usually limited to depths less than 10,000 feet. Also, to locate and follow the cable throughout its length is time-consuming and difficult.

In addition, submersibles are subjected to the hazard of entanglement with the cable system. Searching units attached at the end of a drilling string may be a solution to the inspection problem.

The protection of cables exposed in the surf zone is a problem area. One procedure is to bury the cable beneath the surface to avoid mechanical damage and current disturbance. Severe problems have been experienced with cables laid on a rocky sea bed. Winter storms have stirred up the cables and caused kinks, birdcaging, and entanglements. Huge concrete weights and large chains are used to stabilize the cables. In other cases, the shore cables are protected and weighted down by split cast iron pipe. Divers are used to emplace the awkward and heavy protective pipe sections. The process is time-consuming and expensive.

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V. ELECTRO-MECHANICAL CABLE TERMINATIONS

One of the most complicated and technically difficult engineering interfaces in major ocean systems is the transition from an E-M cable to the vehicle or structure which it serves. It is, therefore, one of the most unreliable.

The primary function of an E-M connectors is to provide electrical and mechanical integrity through an E-M cable junction. It may also provide a watertight interconnection point for a harness at the outboard component and at a hull penetrator. The connector also seals the cable at these enclosures and also prevents the cable from being forced into enclosures due to the hydrostatic pressure at various ocean depths. There are many design considerations which apply to E-M connectors. These are as follows:

1. Connector types and sizes
2. Configuration - connector
3. Plug design
4. Receptacle design
5. Pin and socket contact design
6. Fastening - plug to receptacle
7. Sealing - plug to receptacle
8. Connection - conductor to socket contact
9. Insulation and seal - pin contact
10. Insulation and seal - socket contact
11. Seal - cable to plug
12. Electrical requirements
13. Cable strain relief
14. Material selection
15. Corrosion properties
16. Fabricability
17. Safety
18. Strength of mechanical connection
19. Stiffness
20. Thermal properties
21. Cost

Design Practices

The interface with connectors and penetrators has been given low priority in most cable design efforts. The resulting cable configurations impose constraints on hardware design instead of vice versa. For example, cable hardware must fit smoothly into the mechanical strength member of the system (usually an exterior armor) and efficiently transmit all the complicated tension, flexure, and torsional loads imparted to the cable while at the same time isolating the fragile electrical components housed in the core of the system. Because of stress concentrations due to mechanical loads, damage frequently occurs at or near the connections.

Despite the many engineering problems associated with the cable-structure interface, most cable designers are so constrained by the basic cable requirements that they have historically given insufficient

attention to the problems of connectors, penetrators, and other hardware. This problem is, of course, further compounded by the fact that most early cable development was for cables which were to be terminated only at the surface. Cable technology, therefore, has advanced significantly beyond the technology of deep ocean connectors and penetrators, and the connector designer is generally in the position of having to adapt his hardware designs to fit already existing or specified cables. Recent connector design has nonetheless shown areas of cable design in which termination and penetration hardware considerations might be profitably applied. Improved bonding characteristics of insulation materials, more adquate cable waterblocking in the vicinity of connectors, and improved flexibility to allow handling during connector mating operations are needed.

Cable Connectors and Other Hardware

A dry submarine connector is one designed to be mated in the relatively clean and dry conditions prevailing above the surface of the sea, after which it can be subjected to immersion and hydrostatic pressure. The military specified dry connectors under MIL-C-24217, MIL-C-22249, and MIL-C-22539 use O-rings to seal the water out of a hard shell compartment.

To provide the expanded hardware technology necessary to fully utilize existing high-strength, high-power E-M cables, a program is being conducted to develop both a wet and a dry connector system capable of carrying 360 kilowatts of three-phase, 4160 VAC power to depths of 6,000 feet, under mechanical working loads of 12,000 pounds.

The original concept study included the design of the cable itself, and this rather unique opportunity to design the cable and connectors simultaneously proved very educational. Since the primary emphasis was to be on the connector design, the choice of cable configuration was not quite as restricted as might have been the case if it were being adapted to a specific application. In fact, the only real constraints on the cable design were those imposed by the manufacturer's capability. Recent discussions with the cable manufacturer indicate that the three years of experience they have gained now dictate a design that differs only slightly from that originally chosen. They now have the capability to produce the cable with the only real changes in the jacket thicknesses and armor wire size. Some waterblocking would be added, but otherwise the electrical components would be changed very little, and the basic cable structure would not be changed.

What this implies is that once an application is defined, the cable design follows fairly closely; there is little room for adjustment. Even when there was considerable opportunity to design the cable and connectors simultaneously, the cable design promptly resolved itself to a fixed configuration, leaving the connector hardware concept as the principal area for adaptation and compromise. In fact, some portions of the more advanced connectors (such as the penetrator pins and wet make/break contact systems) are almost independent of the cable configuration.

In other areas, however, there can be real conflict in the design requirements of the two systems, and in these cases it usually appears

that the connection hardware must provide the compromise. A good example is the area of structural support for the electrical connections. The connector needs to be very rigid to provide good alignment during mating operations and prevent breakage or bending while in operation, but if the connector becomes too large and massive it can be incompatible with cable handling equipment, or may represent a source of reflections for shock loads in the cable or otherwise upset the cable dynamics. The solution is to incorporate flexible strain relief and damping into the connector cable termination design.

Thus, it appears that the connectors and other attached cable hardware offer the greatest opportunity for design flexibility of any of the overall E-M cable system components. Part of the reason for the design flexibility is simply that E-M cable hardware has not been as thoroughly developed as the cables themselves. The state of the art in cable terminations such as connectors, penetrators, swivels, strain reliefs, and conductor breakouts is considerably behind the state of refinement associated with the cables, especially as regards high power. There are several commercial sources capable of designing and manufacturing high-strength, high-power E-M cables for deep ocean use, but the choice of associated hardware is very limited and is largely untested or unreliable. Some examples of operational systems follow.

The NCEL DOTIPOS and Seafloor Deep Corer are fairly typical of present applications of E-M cables requiring high power and high strength. It is significant that neither connection system is very flexible, and both must be installed in air.

The inability to make reliable wet connectors precludes some desirable installation and construction techniques and adds unnecessary handling requirements for the cables. For example, the NCEL SEACON I structure was towed to the site with power cables attached and floated astern on spools because there was no reliable way to attach the cables underwater at the site. Poor reliability of high-power connection hardware, combined with the inability to attach or repair the connector and penetrator hardware in the field makes cable reliability even more critical. If a cable defect could be simply removed and replaced with a connector while at sea, many cable expenses would be reduced and overall system down time would be greatly curtailed.

In applications requiring lower voltage or somewhat less strength, the connector hardware has proved to be more successful. Most of the smaller items are fully potted in, relying on the strength of the bonding by epoxy, polyurethane or neoprene compounds to provide support for the electrical components, waterblocking of the cable, and a smooth grip on the cable strength member. The units are simpler, smaller, more reliable, and expendable if required. Many are field-installable. These are generally similar in design to those described in Reference 1 and are primarily used for carrying signals or low-level power. Their primary vulnerability lies in the care in handling exercised by deployment crews.

"Wet" connectors have experienced much more difficulty than dry connectors because of the complexity of the mechanism used to wipe seawater from the male pins as they enter the female half. Experimental systems do function reliably at shallow depths for the first two or three matings, but then seawater leakage begins to degrade the mineral oil

dielectric and the oil must be replaced. A promising mechanism for making the electrical contacts underwater has, however, been developed for a low-voltage connector application by the Crouse-Hinds Company under contract to the Mare Island Naval Shipyard.

The use of pressure-compensated, oil-filled volumes provides the ability to assemble or disassemble the connectors for repair in the field not provided by potted connectors. Installing a heat-shrink boot over the cable end is also fairly time-consuming and complicated, but it is effective, and is easy to install and repair on a wide variety of cables. It also offers considerable compliance, so that relative motion between the cable armor and the internal conductors under pressure and other cable loads can be tolerated without breaking the seal.

In addition to still being in the experimental or early prototype stage, these large-scale connectors have other basic limitations. They are large in size so that they cannot be handled over drums or sheaves. They are heavy, even in water, so that they require special handling systems to allow underwater connection by divers or submersible.

Reliability

Reliability of an item of equipment is the probability that the equipment will operate satisfactorily for a given interval of time (or number of cycles) when used under specified operating conditions and maintenance programs.

Maintainability is the probability that a failed item of equipment will be restored to operating conditions in not more than a specified interval of down time when maintenance and administrative conditions are stated.

Quality control is the set of disciplines and techniques which ensures that the manufactured item conforms to the design specifications.

The most urgent problem associated with the failure of components subjected to deep submergence pressures has been the control of quality (see Reference 1). This control of quality has been absent during one or all of the various stages of manufacture, assembly, test, handling, shipping, and installation. Certainly poor component design has been responsible for many system failures in past years; however, many failures have been rightfully attributed to inadequate manufacturing and installation quality control. The following paragraphs in this section are addressed to quality control and reliability considerations in connector and penetrator design.

The following is a listing of problem areas that have been identified in past years as failure modes for cable connectors, harnesses, and penetrators:

1. Inadequate bond of the molded connector boot to the cable.
2. Inadequate bond of the molded connector boot to the connector shell.
3. Voids in the mold boot of the connector.
4. Damaged cable jackets in the mold cable clamp area, especially in neoprene-molded boots where the cable is held in the mold.

5. Cold soldered joints at the conductor-to-socket connection.
6. Damaged springs in the socket contacts.
7. Damaged coupling ring or receptacle threads.
8. Improper mating of the plug to the receptacle, thus not allowing the proper interface seal to be made.
9. Chipped or cracked contact insulator materials.
10. Bent pin contacts.
11. Porous or cracked receptacle-to-component weld.
12. Damaged or scratched O-ring seal surfaces.
13. Damaged or improperly molded O-rings.
14. Improperly positioned or sized polarizing key.
15. Oversized (too thick) pin contact gasket.
16. Improperly bonded pin contact gasket.
17. Conductor fatigue failure inside the connector.
18. Conductor kinking and breaking in the cable harness.
19. Out-of-spec plug and receptacle dimensions.
20. Conductor breakage due to high impact loads on the cable or a sharp cable bend radius.
21. Short circuit due to foreign materials at the plug-to-receptacle interface.
22. Swelling of seal and gasket materials due to the use of improper cleaning solvents.
23. Dielectric withstanding voltage breakdown of contact insulations.
24. Short circuits at the conductor-to-conductor termination due to foreign materials in potting compounds.
25. Loss of plug-to-receptacle seals due to foreign particles on the seal surfaces.
26. Conductor breakage due to axial tensile loads on the harness.
27. Dislodge keys in the receptacles resulting in loss of polarization.
28. Inadequate spacing between conductor terminations (movement during molding operations) in plug or receptacle which leads to electrical failure when cable seal is flexed or subjected to sea pressure.
29. Relaxation of the springs on the socket contacts with use to the point where contact surface becomes critical and leads to eventual electrical burn-out.
30. Electrical failure resulting from flooding into conductor termination area when female portion is exposed to sea pressure as a result of no protection with pressure-proof covers, and also via cable jacket permeability.
31. Corrosion of contact surfaces resulting in a critical potential drop across the contact surfaces, resulting in eventual burn-out.
32. Failures resulting from general lack of quality control during manufacture which were undetected due to inadequate testing and inspection following fabrication.

33. Electrical degradation of connectors resulting from stress cracks developing in plastic-bodied connectors during manufacture or in service.
34. Failure of threads in plastic-bodied connectors due to in-service handling.
35. Plastic plug coupling ring failure due to impace forces in service handling.
36. Excessive molding flash in rubber connectors in the plug-to-receptacle seal areas resulting in seal failure.
37. Variation in durometer hardness and/or fit between molded rubber plug and receptacles, resulting in seal failure.
38. Seal failure of all molded rubber connectors following mating and unmating in arctic conditions.
39. Pin contact damage at installation or in service due to inadequate protection provided by the receptacle shell.
40. Socket contacts improperly positioned in plug insulator, preventing proper electrical contact with the pin contact.
41. Wear through of the cable jacket due to improper support on the vehicle resulting in flooding of the harness.
42. Improper crimping of the contact to the conductor resulting in an eventual open circuit.
43. Improper termination of braided shields resulting in braid ends piercing conductor insulation.
44. Plug-to-receptacle seal failure due to use of improperly sized O-rings.

The list above identifies 44 common causes of connector failure. The result of any of these failures is the loss of one or all circuit functions. Figure V-1 shows the effect of connector reliabilities if multiple connectors are required for overall system performance. Today deep sea equipment such as the DOTIPOS, Seafloor Deep Corer, or surveillance arrays may use as many as a hundred or more connectors. Each of these connector/cable assemblies and particularly the main electromechanical support cable must function to make the system operable. It is shown in Figure V-1 that a deep sea system containing only 40 connectors would have an overall reliability of 98 percent if each connector had a 99.95 percent inherent reliability. Actually, the reliability of today's deep ocean connectors probably does not exceed 99.0 percent and from Figure V-1 a system with 40 connectors would have a reliability, at best, of 80 percent. If 200 connectors were used in the system the overall reliability would be less than 10 percent.

Manufacturers

The matrix given in Table V-1 indicates the types of connectors made by the various U. S. manufacturers. Table V-1 provides identification of available connectors for 13 U. S. manufacturers.

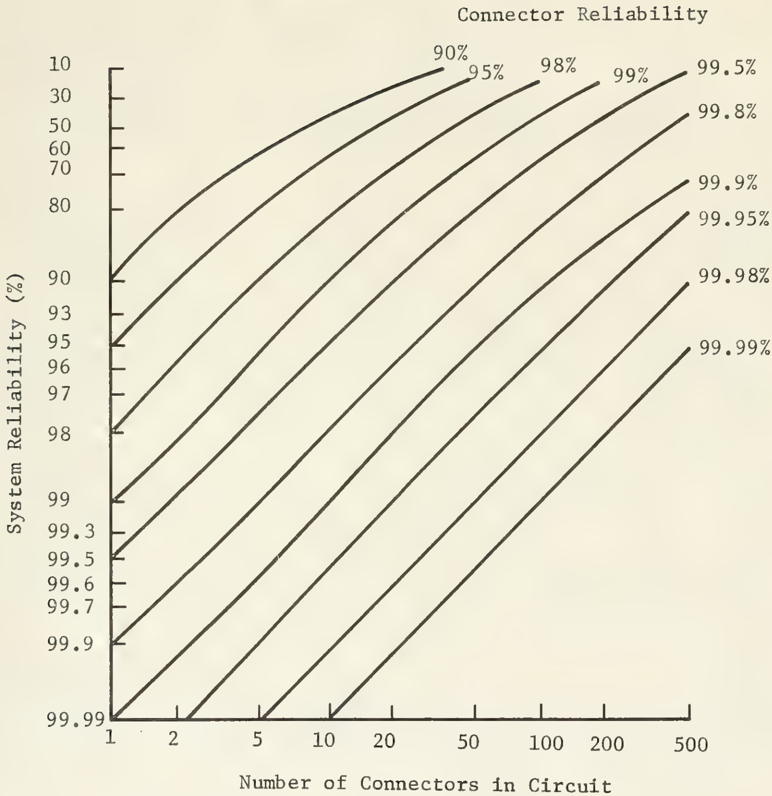

Figure V-1. System reliability with respect to connector failure.

Table V-1. Types of Connectors

Manufacturers	Metal Plug and Receptacle	Molded Rubber Plug and Receptacle	Plastic Plug and Receptacle	Underwater Disconnectable	MIL-C-24217	Pressure-Balanced Oil-Filled	Electro-Mechanical
Amphenol Connector Division	X						
Brantner and Associates	X	X	X			X	X
Burton Electrical Engineering	X						
Crouse-Hinds Company				X			
Electro Oceanics, Inc.	X			X			
Glenair, Inc.	X	X	X				
ITT Cannon Electric	X				X		
Joy Manufacturing Company		X					
Kintec, Inc.	X		X				X
Marsh and Marine	X	X	X				X
D. G. O'Brien, Inc.	X				X	X	
Southwest Research Institute	X			X			
Viking Industries, Inc.	X				X	X	

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VI. MAINTENANCE AND REPAIR OF ELECTRO-MECHANICAL CABLES

Any decision to repair or replace damaged electro-mechanical cables will probably be based on strategic, economic, and mechanical reasons. Although splicing and jointing operations usually require several days to complete, require specialized personnel, and rather sophisticated equipment, repair of a very long cable would still be more economical than replacement. Secondly, time is a factor when the damaged cable is of strategic importance. This could determine whether the cable would be repaired or replaced. Thirdly, all repair methods increase the diameter of the cable in the joined area and this creates a problem when the cable is run over sheaves or stored on a drum.

Storage of Cables

Many types of thermoplastic and thermosetting elastomers are being used for the outer covering, or jacket, of electrical and E-M cables. These materials have been chosen for their mechanical and physical properties and for their environmental resistance. Because these materials are organic, storage conditions for them include: (1) avoid an area which is either dry and cold or warm and humid; (2) avoid long exposure to sunlight and heat; (3) avoid contact with solvents, oils, acids, and bases; and (4) avoid exposure to ozone by storing them away from operating electrical equipment.

Coiling.[1] A cable is coiled with one twist in the cable for each turn of the coil. It is generally easier to fake or coil a cable in the direction to open the armor (clockwise coiling for left-lay armor).

Reeling.[1] With reversed-lay armors, one armor will tend to elongate and the other to shorten with each turn of the coil. This results in an extremely lively cable that is difficult to control. For this reason, double reversed-lay armored cables should be handled in reels.

Tank Storage.[2] Cable ships will have three or four cylindrical tanks for storing cable. Every cable tank is usually fitted with a truncated cone in the center to fill up unusable space and prevent inner turns of cable from slipping down into the center and from jamming or forming a kink when lifted.

A crinoline is sometimes used to guide the cable almost vertically from the level of the fakes to a bellmouth over the center of the tank when it is lifted in paying out and to prevent turns from flying up and possibly causing a kink.

Ocean Storage.[3] A sandy bottom area of the ocean floor can be used to store cable. The cable is payed out in a straight course for which accurate geographic positions can be obtained.

Jointing[4]

Jointing generally refers to the process of making a connection between two conductors and then insulating it.

For nearly 100 years conductor connections have been made by the scarf-joint method, which can be used even when the two conductors are radically different in size. The method has the added advantage of producing only a slight increase in the diameter of the connection.

Assume two ends of armored cable have been made available for jointing and splicing. On one end the sheathing wires and the jute bedding underneath are unlaid or opened out for about 40 feet. The exposed core (conductor plus insulation) is cut away, except for 3 to 4 feet. On the other end the sheathing wires and the jute bedding underneath are unlaid for about 8 feet, and 2 feet of the exposed core is cut away. The insulation is stripped off with a sharp knife for about 3 inches at both ends of the core. The copper strands are untwisted, with care not to break any of the wires, and each wire is thoroughly cleaned with emery cloth; the wires are then retwisted in the original direction into a strand. The strands of both cable are soldered for about 1 1/2 inches from the end and quickly cooled, and both soldered ends are filed to form a scarf or bevel 1 inch long. They are then clamped into the jointer's tray, which is fitted with two small upright vises for holding and properly locating the scarfed ends.

The scarfed ends then are temporarily bound together by four strands of 0.010-inch copper binding wire (held so as to form a stranded tape) applied in an open helix. The scarfs are then soldered, with care taken that the solder flows between the abutting surfaces. The temporary binding is stripped off, and the soldered surface is smoothed with emery cloth. The soldered surface is then wrapped with four strands of binding wire so that it is entirely covered, with the binding strands close together but not overlapping. This binding is then completely soldered. Next, another wrapping of four strands of binding wire is applied in the opposite direction, over the full length from one vise to the other. This second wrapping, secured by soldering for about 1/2 inch on both ends, serves as a guard wire in case the electrical joint separates.

<u>Insulation - Universal Method</u>. The method formerly used with gutta-percha insulated cables is not suitable for polyethylene. As a result, a method has been developed with a special tape that can be used on any kind of insulation. It is sometimes called the "universal" method and utilizes materials obtainable from the Simplex Wire and Cable Company in Cambridge, Massachusetts. It can be used in the jointing of gutta-percha, rubber, polyethylene, or telecothene insulations to themselves or to one another. The procedure is the same for any of the insulations except that with gutta-percha the K540 cement is not used on the scarfs.

The end of the insulation is prepared by tapering it over a length of approximately 3 inches, starting approximately 1/4 inch from the edge of the conductor joint. The surface of the scarf is made smooth and symmetrical by scraping with a knife. Loose insulation particles or dust must be removed from the surface.

On rubber or polyethylene insulation the K540 cement should be thin enough to apply with a small brush. If the cement is too thick it can be thinned with toluol. A second coat is applied after the first one is slightly dried. The scarfs are then placed in an electric heater, where the temperature is brought to 212°F. The scarfs are allowed to cool to

room temperature. The joint is then ready for insulation with K580 splicing tape. This tape should be prestretched and released during the application to avoid residual tension in the completed insulation joint. The tape is used to build up the joint to approximately the diameter of the original insulation over the conductor. The joint is then covered with one layer of polyvinyl chloride tape with some overlap. Three layers of neoprene tape are wound over the polyvinyl chloride tape, after which the joint is ready for protective coverings.

Injection-Molding Method. The method described above is perhaps the simplest, and has been used by the telegraph cable companies in their ordinary repairs to telegraph-type cables. However, because of the more critical nature of the transmission characteristics of wide-frequency telephone-type cables, and also because of their high voltage, this method has not been generally used in telephone cables. Instead, the conductor joints are insulated with an injection-molding machine.

In this process the conductor joint is made by brazing, and the conductor is then held inside a carefully machined mold into which molten polyethylene is injected at high temperature and pressure. After the polyethylene has filled all the voids between the cable and the inner surfaces of the mold, the temperature is lowered and the mold is removed, leaving the polyethylene insulation neatly fused into the balance of the cable insulation. After the feather edges which appear at the mating surfaces of the mold halves are smoothed down with a sharp knife, the final produce is practically a homogenous transition from conductor-joint insulation to basic-cable insulation.

The dies for the molding heads are machined to meet the outer diameter under the basic cable insulation; hence, different dies are required for each size of cable core. The joints are generally x-rayed for possible inclusion of foreign matter and voids. This method produces a result equivalent to a factory-made joint. It is, however, somewhat slower than the universal method described above and requires special equipment.

Splicing[5]

Splicing is joining the armor wires of two lengths of armored cable in such a manner that the full tensile strength of the cable can be passed from one length to the other. The method generally followed in replacing the armor is referred to as the "overlapping splice". In preparing for the conductor joint (see above), 40 feet of sheathing and jute yarn are unlaid on one end and 8 feet are unlaid on the other. These unlaid portions will be referred to as the "long end" and "short end", respectively.

The jute yarn on the short end is wrapped round the core and secured with yard seizings. Any remaining bare core should be wrapped with the jute yarn from the long end. The short-end sheathing wires are then laid spirally over the jute bedding, with all wires abreast in their correct order and secured with yarn seizings at about 1-foot intervals. Next, the long-end sheathing wires are laid on spirally, overlapping the

short-end wires for an appreciable footage, and secured at intervals with soft-iron wire seizings. The entire length of the splice is served with tarred spun yard, applied with serving mallets.

A splicing tool is used for laying up the sheathing wires. It is a steel plate in the form of two half-circles, each with a handle, with notches in the rim. It opens in the middle so it can be set in position across the cable. Once the sheathing wires are placed in their respective notches, it is closed and fastened by a set screw. It is then worked around by the handles in the direction of the lay forcing the sheathing wires spirally around the cable in their proper order. The tool is pushed along the cable as it is rotated.

Sleeves

Sleeves have been used in cable-jointing processes, both as load-carrying devices in the armor and for the purpose of maintaining electrical continuity in the conductor. In the latter case, the mating ends of the conductor are thoroughly cleaned and then slipped into the opposite ends of a carefully sized copper sleeve, which is then squeezed by a hand crimping tool. Two or three crimps on each half of the sleeve are usually sufficient to provide adequate contact and a grip on the conductor that will carry the very small tensile load. After the conductor is sleeved together, the joint is insulated by any of three methods described above.

Sleeves used as load-carrying members are usually of stainless steel. They are used principally for the central tensile-carrying steel strand of the nonarmored-type cables. Generally, these sleeves are somewhat heavier than the copper sleeves mentioned above, but the principle is basically the same.

The Simplex Wire and Cable Company experimented with steel sleeves in nonarmored-type cables. They found a single 1-inch long crimp on a 7/16-inch O.D. sleeve over a 0.214-inch strand was able to carry a tensile load of 4,200 pounds. These were tested to destruction; instead of pullouts, the usual mode of destruction was the fracture of one or two steel strands at the location immediately at the entrance to the sleeve. This indicates the high friction grip developed in these sleeves.

A method[6] for splicing caged armor coaxial cable (3-D multiplex array cable) has been developed by Simplex Wire and Cable Company. The splice requires two men, two and one-half working days to complete. Briefly, it consists of:

1. Preparation of the work area
2. Preparation of the cable ends
3. Brazing the inner conductor
4. Molding of 0.18-inch-diameter insulation
5. Brazing the return tapes
6. Jointing the shielding tape
7. Patching the belt
8. Sleeving the armor wires
9. Molding the armor bedding
10. Patching the outer jacket

Hotsplicer Corporation[7] produces portable molding presses for making vulcanized splices in electrical cables up to 5 inches in diameter. These presses can also be used to rejacket damaged electrical cables.

Earlier development work on equipment and procedures for jointing polyethylene-insulated submarine cables is described in Reference 8.

The British[9] are using aluminum conductor, aluminum-armored cables for electrical distribution use. The jointing techniques for these cables are similar to those which use copper conductors except that stranded aluminum conductors are not heated by heat guns or gas torches. Instead, these conductors are heated by pouring molten solder (basting) over them until they become hot enough to melt a solid "stick" of solder. Compression jointing is used on large single-core high-tension cables.[10]

Preventive Maintenance of Cables

No formalized procedures for the preventive maintenance of submarine cables exist as standard military procedures.

A routine preventive maintenance program has been proposed.[11] This program would consist of electrical and visual checks.

Electrical checks are performed to obtain a history of cables condition and to localize faults. Two methods are used: (1) the Wheatstone bridge is used to determine dielectric resistance, conductor resistance, and capacitance between conductors and between conductors and ground; and (2) pulse echo equipment, which provides a quicker and more accurate means of pinpointing the location of minor and major faults but is limited in range.

Visual checks are performed to obtain a history of cable condition and rate of deterioration. They also include a survey of cable position and inspection to the maximum safe depth for divers.

Items which need to be included in maintenance programs are: expected lifetime of materials, corrosion prevention systems, inspection routines, cost analyses to determine if repair or replacement is warranted.

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VII. MANUFACTURING

There are several manufacturers of E-M cable in the United States. Foreign manufacturers supply the majority of the market of E-M seafloor cables.

USA

Simplex Wire and Cable Company
United States Steel Company
Vector Cable Company (Division of Schlumberger Technology Company)
South Bay Cable Company (Division of Consolidated Products Corporation)
Rochester Corporation
Boston Insulated Wire and Cable Company
International Telephone and Telegraph
General Cable Corporation
Phelps Dodge Copper Products Company
Anaconda Wire and Cable Company

Foreign

General Wire and Cable Company, Ltd. (Canada)
Universal Wire and Cable Company, Ltd. (Canada)
Pirelli General Cable Works (England, Italy)
Standard Telephone and Cable (England)(Subsidiary of IT&T)
British Insulated Callender's Cable, Ltd. (England)
AEI Cables (England)
Sumitomo Electric (Japan)
Furukawa (Japan)
Showa (Japan)
Fujikura (Japan)

American companies have supplied all types of E-M cables, i.e., ocean, working, and structural, on special order. Some manufacturers do list standard types of cables in their catalogs but these are designs which are available and can be supplied by that manufacturer but very few cable applications are standardized enough for the manufacturer to stock large quantities of electro-mechanical cable.

Foreign Manufacturers

The manufacturing of E-M cable had its inception in Europe. Some of the larger cable companies in Europe have produced cable for many more years than any American manufacturer. This fact, in some instances, has proved detrimental to the European cable industry. The major manufacturers tend to be hesitant to change the old methods of manufacturing cable. Some manufacturers are still using materials which American manufacturers have stopped using ten or fifteen years ago. On the other hand, the European

manufacturers have become very selective in the types of cables which they will manufacture in their plants. This is most likely due to the labor situation and they have chosen to manufacture those cables which are most economic to their company. An example is the British Callender's and Insulated Cable Company which, at one time, was one of the largest ocean cable manufacturers but now only manufactures short lengths of cable for river crossings. Pirelli, on the other hand, has shown quite an aggressive attitude in the cable market. The Japanese manufacturers have been in the business only since the Second World War. This means that all of their equipment and machinery is relatively new and automated. Also, the labor situation in Japan has necessitated automated cable manufacturing. With automated machinery, cable can be made much quicker, and the lower labor costs make the Japanese cables very competitive. One American distributor for Japanese cables claims to possess the entire oil industry market in the Gulf of Mexico using Japanese-manufactured signal and power cables for shore-to-platform runs.

Manufacturing Procedure

The manufacturing of E-M cable requires several steps which are basically the same for each manufacturer. Differences do occur between companies production capability, such as maximum size or number of conductors, etc., which is usually the result of the type and age of the machinery used, but each company performs the following steps.

Stranding. The stranding process in cable making consists in passing individual metal wires through the machine which then bunches them into groups of seven or more small wires which become conductors of various AWG sizes. These machines can handle various types of material such as copper or aluminum or any other ductile metal. These conductors are then used to form coaxial cables or they go through an extruding machine which covers them with insulation materials. Some of the materials used for extruding insulation over these conductors are vinyl, polyethylene, polypropylene, nylon, rubber, neoprene, or teflon. These extrusion machines can put almost any thickness of insulation on the conductors while simultaneously measuring and monitoring and testing the cable.

Cabling. The next process is called cabling. The machine used for this is referred to as a planetary machine in that it uses planetary twining bobbins which combine the conductors into cable assemblies, on some machines as great as 7 3/4 inches in diameter. Larger machines can simultaneously assemble in excess of 100 concentrically-laid conductors. Some of these machines also have a step in which void filling can be performed at this stage. Various types of void filling are available depending on the type of waterblocking that is required.

Jacketing. The jacketing process involves covering the conductors with either a thermoplastic or thermoset covering, rubber or neoprene which is extruded over the cable.

Armoring. Armoring does not occur on all cables, but on those with outer armor the machine produces any number of outer armor wires of various materials and diameter, usually with a preformed construction. Cables ultimately resulting in 8.0-inch diameters are possible on some machines.

The cable is then either stored in large tanks until it is ready to be loaded or ready to be used or it has terminations molded and takeouts molded according to specifications. Some of the limiting factors for various manufacturers is the maximum outside diameter of a jacketed cable or the maximum outside diameter of an armored cable.

VIII. SUMMARY

After decades of specialized development for bottom-laid ocean communications cables, an exponential increase in the number of uses and types of applications for E-M cables has left the technology behind the demand. In this study, areas deemed important to cable users were researched to determine what the technological capabilities in the field of E-M cables are today. One result of this research is the identification of areas lacking in development, or needing improvement, from the point of view of users, designers, and even the manufacturers.

An E-M cable system starts with a very specific application born out of the necessity to use a single cable for both the electrical and mechanical functions, instead of separate cables to perform these functions independently. The two primary areas of concern are the electrical design and the mechanical design of the cable. It is from these divergent points of view that problems may be generated. Writing specifications for a cable is not an easy task in view of the real complexity of something seemingly as simple as a cable. Often the user or designer of the cable does not provide the proper design or specifications to the manufacturer, or the cable may be used for a different purpose or under different conditions than those for which it was originally intended. Symposia have been suggested to exchange cable information, while others have suggested that standards and procedure should be established based on past E-M cable experience, future applications, and potential problems. Others have suggested increased efforts toward the investigation of advanced methods of powering, controlling, and communicating for deep sea systems without cables, such as ultrasonic transmission, self-contained power sources, and fiber optics.

This study found that a large amount of basic information is still lacking. Thus, the designer of a cable system today must still spend an excessive amount of time investigating such things as materials and manufacturing capabilities, or he must rely on the manufacturer to supply him with a cable based on a general specification, or use trial and error methods. The various areas of the study are summarized briefly to indicate the deficiencies and the proficiencies of the technology. The current state of the art of E-M cable technology, problem areas, and requirements are summarized below.

Electrical

The area that limits any possibility of standardization of cables is the electrical requirements of each application. Each user of an E-M cable has very specific power requirements and even more stringent signal requirements, which are generally inflexible for any one system. The size and number of the conductors, the voltage and frequency, and the tolerable power losses are usually unique to each system. Most power and signal requirements are adequately handled by the present technology, with the possible exception of high-voltage transmission. This exception points up an area of need for better conducting and insulation materials. Longer lengths of cable put additional demands on conductors and insulation to achieve a maximum practical transmission distance. The area of exotic

materials such as low temperature and superconducting metals may offer solutions. Another little understood parameter of conducting materials, is their response to stresses imposed mechanically. High-voltage transmission will also require improved dielectric materials. Gaseous dielectrics may ultimately provide the most cost-effective solution.

Mechanical

In contrast to the electrical design which is very specific for the application, considerable latitude exists for the mechanical design of an E-M cable.

Materials. The most widely used material for the strength members in E-M cables is steel, but the weight of steel is the one property which generates the need for investigation of different strength member materials. The use of synthetics as strength members in E-M cables looks very promising because of the following advantages: (1) high strength-to-weight ratio; (2) extreme flexibility; and (3) resistance to corrosion. Complete tradeoff analyses between the various synthetics and metallic strength members have not been performed. This is presently very difficult because of the lack of data for synthetics as E-M cable members. Improved metal alloys and metals are not beyond the scope of application in E-M cables, but those alloys and metals with the most desirable properties, such as corrosion resistance, high strength and better fatigue properties are presently too costly for most applications.

Failure Mechanisms. A very deficient area which falls largely under the mechanical function of the cable is the lack of understanding in the area of failure mechanisms. Since most cable applications fail due to some handling problem or to some mechanical property of the cable, improvements in design, materials selection, and handling will follow when the failures are pin-pointed and understood. Four problem areas of E-M cable failures are kinking, fatigue, inadequate splicing techniques, and low reliability of terminations. The kinking mechanism and the conditions under which kinking occurs are not well understood. Fatigue tests on various types of cable constructions and various materials have not been made so that it is impossible to predict and compare the working lives of E-M cables to develop selection criteria for the best cable for a particular job. Analyses are also lacking in the area of dynamics, snap loads, and rotational response of the cable to torque and tension, elongation and creep, elasticity and fatigue strength. Seawater that permeates the cable jacket and insulation causing hosing of water along unblocked conductors to termination devices has been responsible for many undersea system failures.

Terminations

Present cable terminations lack reliability even though there are many suppliers of connectors and penetrators. Although these suppliers can deliver the basic types of underwater connectors, stronger water-impervious and more reliable methods of terminating E-M cables are needed.

Maintenance and Repair

There has been much development in field repair techniques for bottom-laid communications cables. The present repair methods are not directly applicable nor is the time required to complete repairs acceptable to the newer demands and applications of E-M cables. What is needed is a quicker technique to join conductors and splice armor at sea to produce a splice which is approximately the same diameter as the original cable. This presently is not possible, except on factory repair jobs, which is still a time-consuming process.

Handling

Handling E-M cables falls into three categories: (1) factory to ship; (2) on board ship; and (3) deployment in the ocean. Each category can be examined to find technical deficiencies in the procedures and techniques for handling E-M cable. Mechanical cable technology is not directly applicable to E-M cable, and it is for this reason that the criteria for selecting basic hardware (such as winches) and procedures that should be used to handle E-M cable are not well understood. The problems with handling are first the lack of experienced personnel who know the cable limitations; and second the cable itself. Either, not enough is known about the cable or, it is not designed with the eventual handling procedures in mind. New developments in cable design are concerned with deployment problems, but the system designer has done little with regard to the storage and handling steps prior to deployment. Special hardware and equipment may also have to be specified, ordered or built at the time the cable is specified and designed. The handling problem solution is also dependent on understanding the failure mechanisms.

Some people have handling problems, others do not. This indicates that an expertise does exist, at least for certain applications and for certain types of cable. Until this limited expertise is somehow distributed to more people, problems will continue to occur. Handbooks, manuals and papers outlining cable operations in detail are needed.

Testing

Underlying all of the above technical areas is the need for an increased capability in specification writing and testing. The only method that can determine analytically whether specifications were inadequate or whether some other deficiency caused the cable to fail is an adequate testing program. Such a comprehensive testing program does not exist.

Basic materials testing programs are not keeping pace. The newer, more exotic synthetics, particularly the PRD-49 group, have not been tested to determine their advantages and disadvantages. Materials are not being tested in such a way that the results are related to their ultimate application. Failure mode testing must be developed to provide results applicable to the use of the cable.

Testing at the manufacturing stage is inadequate because the suppliers generally have poor facilities and poor guidelines. The only parameter a manufacturer supplies as standard is breaking strength. The

testing of cables is not being carried out to determine adherence to specifications, because the most critical cable parameters have not been determined so adequate test procedures to evaluate these parameters can be developed.

Long-term testing to determine the effect of extended loading on cables is also lacking. New designs need to be tested and failure prevention solutions evaluated. The manufacturers cannot, or are reluctant to provide this testing capability without a marked increased in cable costs.

IX. RECOMMENDATIONS

1. It is recommended that efforts be undertaken that will provide cable users with adequate guidelines to write E-M cable specifications. Guidelines include such things as design criteria, materials properties, manufacturing capabilities, and sample specifications. This could result in a military specification for E-M cable, a handbook, or both.

2. An E-M cable testing program should be developed. Testing theory, methods and facilities must be examined with the aim of developing a military specification covering cable testing during and after manufacturing. Facilities must be adequately equipped within the Navy system to handle testing. These tests are presently so expensive that most users do not have them done. Failure mode, specification and long-term testing of E-M cables should be conducted.

3. Extensive development is recommended in the area of failure mechanisms for cable applications. With the lack of data on behavior of actual cable usage—a program of controlled laboratory tests should be conducted subjecting the cable to as many of the expected conditions as possible. Analytical and empirical data should be obtained to categorize and predict failures due to such things as kinking, fatigue, torque imbalance, snap loads, creep, dynamic loads, strumming, and water permeation.

4. A cable handling handbook is needed to disseminate the scattered knowledge of handling E-M cables. There is no existing reference for Navy or civilian contractors to use for planning and executing the cable deployment operation. This is needed if deployment operations are to increase in the Navy, especially if they are to be performed by many different groups. Included in this handbook should be sections on handling equipment, platforms, ships, and techniques. The use of electrical cable handling devices and mechanical cable handling devices to handle E-M cable should be evaluated.

5. It is recommended that connector development be increased to improve present commercial capability and reliability of wet and dry connectors, as well as the advanced requirements. In addition, other termination hardware should be examined such as E-M swivels, armor terminations, and conductor breakouts.

6. Strength member data are lacking in the newer synthetic materials. Testing programs to generate these data and present them in comparative tables with the present materials is recommended. Neutrally buoyant cables using synthetics should be developed.

7. A program to develop improved field splicing techniques is recommended. A portable device which can repair armored cables within the time limits acceptable to covert installations must be developed. In addition, a maintenance program should be drawn up for all cable users to cut costs of cable emplacement and system down time.

8. It is recommended that high-voltage conducting materials and improved dielectrics for cable applications of the type projected for Navy use be developed.

9. More cost-effective corrosion prevention techniques than the use of nickel-steel alloys and titanium need to be developed and subjected to long (measured in years) ocean conditions for verification.

A comprehensive outline of E-M cable technology is shown in Table IX-1 to provide an at-a-glance comparison of the areas of recommended research with those more advanced as determined by this state-of-the-art study.

Table IX-1

ELECTRO-MECHANICAL CABLE PROGRAM

- HANDLING
  - Manufacturing
    - Storage
    - Shipment
  - Logistics
    - Shipment *
    - Transfer
  - Shipboard
    - Storage
      - Winches *
      - Tanks *
    - Tensioning
      - Constant *
      - Motion Compensating *
    - Hardware
      - Sheaves
      - Line Stopper *
      - Line Fastener *
      - Crane/Boom
    - Procedure *
- PROPERTIES
  - Electrical
    - Conductors
      - Power *
      - Signal
    - Insulators
      - Liquid
      - Solid
      - Gas *
    - Shields
    - Component Configuration
      - Cabling
      - Mechanical Deformation *
      - Fault Paths
  - Mechanical
    - Strength Members
      - Metallic
      - Synthetic *
    - Armor
      - Metallic
      - Jacketing *
    - Component Configuration
      - External
      - Internal
      - Torque Balanced *
      - Buoyancy *
- TERMINATIONS
  - Mating Mechanism
    - Penetrators
    - Connectors
      - Wet *
      - Dry *
    - Strain Relief
  - Swivels
    - Mechanical
    - Electrical
      - Slip Ring *
- MAINTENANCE & REPAIR
  - Maintenance
    - Inspection *
    - Frequency *
  - Repair
    - Factory
    - At-Sea
      - Jointing
      - Splicing *
- TESTING
  - Failure Modes
    - Kinking *
    - Fatigue *
    - Corrosion *
    - Abrasion *
    - Snap Loading *
    - Dynamic *
    - Cyclic Load
      - Strumming *
  - Long-Term *
  - Specification *

*Areas Requiring Additional R&D

X. APPENDIX

History

Early developments in submarine cables had their origins in the British Isles. Cut off from the European mainland by the English Channel, England had a pressing need to establish communication with Europe. Michael Faraday, soon after the discovery of gutta percha, suggested that this raw Indian rubber substance might be used as an underwater insulator for submarine cables.

The famous Gutta Percha Company was incorporated in 1845 and learned the processes of extruding gutta percha on copper, and in 1848 a two-mile length was tested in the ocean prior to being put to use in a wet railway tunnel. This first application of a submerged electrical cable produced grandiose schemes for promoting international communications using submarine cables.

The first submarine cable was laid between England (Dover) and France (Calais) in 1850. The cable used was gutta percha insulated copper wire. The cable had to be weighted because of the buoyancy effect of the gutta percha. Lead weights were attached every 125 yards. Telegraphs were undecipherable due to a phenomenon caused by the capacity of the cable and not understood by these pioneers.

In 1851 the first successful crossing of the English Channel with a workable telegraph cable was completed using four #16 copper wires, each insulated by gutta percha and armored with steel wrap. The armoring of gutta percha insulated copper wire was made possible by a development in 1840 by a technique for laying wire rope over a hemp center.

The patent was later shown through litigation to cover the armoring of gutta percha. This monopoly lasted until the patent ran out in 1854. Some other companies attempted to use hemp armor over gutta percha, but without success. Almost all of the submarine cables laid before 1865 were supplied by the Gutta Percha Company.

In 1855 several cables were laid in the Black Sea for the British and Ottowan governments who were allied with the French against Russia in the Crimea. Because of their urgent need only the shore ends were armored with unprotected gutta percha in the deeper water.

These were the first submarine cables used for military purposes. The cables were laid by ELBA, the first ship to be fitted with a circular tank, cone, and crinoline, the chief components of cable storage used today to assure a constant rate of pay out for the cable, and avoiding fouling of the cable by insuring its egress from the center of the tank.

Although the vulcanization of rubber was invented by Goodyear in 1839 and continuous vulcanization of rubber around a conductor was accomplished in 1845 by a chemist named William Hooper, rubber insulation was not used extensively in the ocean because of its partial solubility in seawater. Rubber was, however, superior to gutta percha in some areas such as resistance to Toredos and extreme temperature ranges. The first rubber-insulated cable was laid in 1865 between India and Ceylon. It was not until 1926 that a deproteinization process discovered by Simplex Company made rubber a practical insulation material for submerged applications.

The first use of deproteinized rubber was between Florida and the lighthouse on Fowey Rocks off Miami, Florida. In fact, gutta percha was widely used as an insulation compound until the late 1920's.

In 1856 the Atlantic Telegraph Company was formed to cross the Atlantic with a telegraph cable. The first attempt in 1857 resulted in failure with the cable breaking in 2000 fathoms of water. In 1858 the Atlantic was actually crossed by a telegraph cable but only 723 messages were carried before failure of the cable.

In 1866 the first successful transatlantic cable was laid in one piece between Newfoundland and Ireland by the steamship GREAT EASTERN. It consisted of a single copper cable insulated with gutta percha protected with wire wrap covered with jute and tar. The return circuit utilized the earth. There were no repeaters, but a Lord-Kelvin terminal device was used to sense extremely weak current pulses.

The first submarine telegraph cables loaded to increase cable capacity were laid by the Danish government between Elsinore and Helsinborge, Sweden. In the early 1920's the Western Electric Company carried out experimental work to increase the traffic capacity of submarine telegraph cables. This led to the development of Permalloy. Permalloy tape was used to wrap cable conductors to load and shield the cable, thereby increasing traffic capacity. In 1924 Permalloy-wrapped cables were put to use. By 1928 the Telegraph Construction and Maintenance Company produced another alloy, Mumetal, which was used similarly to Permalloy with even superior results. Mumetal was also easier to manufacture. The first Mumetal was laid in 1928.

Submarine telegraph cables antedated the invention of the telephone. Although Robert Hooke invented the string telephone in 1667, A. G. Bell invented and patented the first telephone of practical use as late as 1876. Shortly thereafter, the first submarine telephone cable was laid in the English Channel between St. Margaret's Bay, England, and Sangatte, France. The cable had four conductors.

The year 1921 was marked by the laying of the first submarine telephone cable in the ocean other than river or harbor crossings. Three cables were laid between Key West and Havana. These were also the first of the coaxial cables used in the ocean. In 1923 deep water submarine telephone cables were also laid between the California mainland and Santa Catalina Island

In 1938 the first cable insulated with telcothene was manufactured by the Telegraph Construction and Maintenance Company. Telcothene, Telegraph Construction and Maintenance Company's name for polythene, was discovered in 1933 by the Imperial Chemical Industries.

In 1942 the first submarine repeaters were developed by the Research Department of the General Post Office of England as a result of research conducted during the 1930's to increase the traffic capacity of cables and to span long distances with high frequencies by submerged amplifiers. The first repeaters were used in 1943 in the Anglesey, Wales-Port Erin paragutta coaxial cable laid the previous year. These were one-way amplifiers. Nineteen hundred fifty saw the first two-way repeaters used and also the first submarine coaxial telephone cable using submerged repeaters.

Although in 1928 the Bell Laboratories first proposed a transatlantic telephone cable which was to be a single-conductor, continuously-loaded nonrepeatered system, the first such transatlantic telephone cable was not laid until 1956 between Clarenville, Newfoundland, and Sidney Mines, Nova Scotia. The prototype to this cable was laid in 1950 between Key West and Havana. It was a twin cable system, one cable "go", the other "return", with flexible one-way repeaters; 24 channels were available.

In 1952 C. S. Lawton developed a lightweight cable for telegraphy by eliminating the armor, and in 1963 the first lightweight cable was used between Florida and Kingston, Jamaica. The cable was designed in America. In 1961 the first submarine cable with a high tensile steel center strain member was made.

The use of working E-M cables in the ocean is a relatively recent development. The 1950's saw the development of oceanographic sensors that were lowered and raised from shipboard using small diameter electromechanical cable. In the 1960's seismic arrays had evolved into such great lengths that strain members had to be put into the signal cables. The 1960's also marked the beginning of deep-towed instrument packages and sensors such as side-scan sonar. These E-M cables usually used the external contrahelical armor as the strain member with several internal types of conductors.

The technology of working E-M submarine cables has benefited from the science of well-logging. Since the invention of the electric log by Schlumberger in the 1920's, most oil exploration drill holes have had various sensors, tools, and gadgets lowered into them by E-M cable. The logging of oil exploration drill holes is comparable in depths and pressures to working in the sea. In 1972 a well was drilled in Oklahoma to a depth of 30,000 feet. The pressures for any given depth are usually higher than those experienced in the ocean because drill holes are generally filled with drilling muds that have specific gravities higher than that of seawater.

Temperatures are extreme, increasing with depth, contrary to the oceans. The higher temperatures of drill holes present problems which relate only peripherally to ocean work—for instance, in 1965 polypropylene was developed as an insulator.

Extreme corrosion problems of cables are encountered in drill holes, especially where deep wells penetrate salt strata. For instance, salt-supersaturated drilling mud is used to drill through salt formations to prevent dissolving the sides of the bore hole. Conventional cables are used under these severe conditions. External armor is made of standard improved plow steel; the only concession to the hot brine environment is the sluicing of the cable as it is retrieved from the hole—this being more cost effective than using corrosion-resistant materials.

In the early 1940's the Schlumberger Company began using external steel wrapping on cables as a strain member to replace their "rag-line" cables which carried the conductors outside of the internal strain member. The "rag-line" was marked every 100 feet or so with paint as a means of measuring the amount of cable out. In the late 1940's the Schlumberger Company began to use magnetic marks spaced every 100 feet on the cable. These magnetic marks were impressed on the cable by placing both poles of a horseshoe magnet against the cable and simply rotating the

magnet around the cable once or twice. This magnetic mark lasts several months, is easily detected electrically and transduced to ring a bell as each mark passes the sensor, obviating the need for measuring wheels which are vulnerable to slippage.

E-M cable used as structural members in submarine construction is a recent development, probably dating from the late 1960's. The Navy AUTEC range in the Tongue-of-the-Ocean, Bahamas, includes a tri-moor platform from which is suspended an E-M cable to a submerged buoy. This cable is a signal carrier and also supports sensors between the buoy and the tri-moor platform.

In 1969 the deployment of Pacific SEA SPIDER, a tri-moor E-M and mechanical cable structure, was attempted. A cable release opened prematurely, severely kinking the E-M cable, aborting the implantment.

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13. ABSTRACT

A state-of-the-art study was made of submarine electro-mechanical cable technology. These are ocean cables which include electrical cables with special strain members. The purpose of the study was to define areas of deficiencies so that development programs could be initiated in selected areas.

The approach included a literature search, and extensive interviews with electro-mechanical cable manufacturers and electro-mechanical cable users. Engineers and scientists of various disciplines from the Naval Civil Engineering Laboratory participated in the study. Areas of study include: Mechanical Properties, Electrical Properties, Handling, Terminations and Hardware, Maintenance and Repair, Manufacturing, History of Electro-Mechanical Cable Development.

The technological development of submarine electro-mechanical cables dates from the mid-nineteenth century with their use as telegraph and, later, telephone cables. There is, therefore, a voluminous literature on ocean bottom communication cables. The wide use of electro-mechanical cables suspended above the seafloor began within the past 12 years. These cables include electro-mechanical cables deployed above the seafloor and can, with a few exceptions, be included in two categories: structural cables, used as tensile members in support of structures tethered to the seafloor; and working cables, typically deployed and retrieved by winch into the sea from a surface or subsurface platform. A special case of working electro-mechanical cables, oil well logging cables, have technological developments dating back to the 1930's.

Deficiencies are still present and can be generally categorized in the four areas of: design of electro-mechanical cables and terminations, specifications and testing, handling, and repair and maintenance.

Areas of suggested electro-mechanical cable development are: (1) Testing standardization, (2) Specification standardization, (3) Failure mechanisms analyses, (4) Standardize handling methods, (5) Corrosion, (6) Torque balancing, (7) Develop a better field splicing technology, (8) Use os synthetics as strength members, (9) High power transmission, and (10) Terminations such as connectors.

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